University of Southern Queensland

Faculty of Health, Engineering & Sciences

# Reliability-Centred Maintenance Analysis of a Rio Tinto Iron Ore Locomotive Engine

A dissertation submitted by

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in fulfilment of the requirements of

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towards the degree of

**Bachelor of Engineering (Mechanical)**

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# Abstract

This research project primarily aims to develop two pieces of knowledge:

- Identify whether Rio Tinto Iron Ore's (RTIO) current locomotive diesel engine maintenance regime is optimised.
- Identify the failure modes and the risk mitigated by each maintenance task that is performed.

The current maintenance program has been directly transferred from the Original Equipment Manufacturer (OEM) recommendations. As such, RTIO has not developed an understanding of:

- How each maintenance task impacts the reliability of the locomotive fleet
- How much risk each maintenance task mitigates, and whether the task is worthwhile
- Failure modes that are occurring but are not formally addressed in the maintenance management system

Without this knowledge, RTIO cannot be assured that the maintenance resources allocated to engine maintenance are utilised efficiently.

The literature reviewed did not find research that had analysed the maintenance regime applied to locomotive engines operating in a hot, semi-arid mining environment, revealing an opportunity for this research project to contribute to the body of knowledge on diesel engine maintenance.

The project applied the Reliability-Centered Maintenance (RCM) methodology to develop engine maintenance tactic recommendations. The data necessary for the analysis was obtained from a variety of sources, including:

- Senior tradespeople, technicians and engineers
- Computerised maintenance records
- Production delay and failure records
- Component failure analysis reports
- Textbooks and academic research papers on engine failure analysis
- OEM training manuals

The RCM methodology inherently produces a database that details the failure modes and the risk mitigated by each maintenance task, providing a platform that can be continually built on over time. As a result of this database, RTIO now possesses the knowledge necessary to evaluate the failure modes and the risk that is mitigated by each maintenance task, providing the foundation to make informed maintenance decisions as the operating context changes over time.

Finally, the maintenance task recommendations generated by the analysis were compared to the current maintenance tactics in order to establish the optimisation of the current regime. The research project has concluded that the maintenance regime is generally optimised, but a number of minor improvements are identified.

# Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Caleb Mayne

0050084492

Signature

Date

# Acknowledgments

First and foremost, thanks to my wife Lisa, for her support not only this year during the project, but throughout the entire time I have been studying.

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Finally, thanks to my project supervisors, John McArthur (RTIO) and Dr. Steven Goh (USQ) for their regular advice and input since the start of the year.

Caleb Mayne

*University of Southern Queensland*

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# Nomenclature

| | |
|---|---|
| Age exploration | The process of determining the aging characteristics and potential failure modes of equipment if no service life data is available. |
| Applicable maintenance task | A task that addresses the identified failure mode. This term has the same meaning as 'technically feasible'. |
| Default actions | Actions that are employed only when no proactive tasks are technically feasible and worth doing. |
| Effective maintenance task | A task that reduces risk to acceptable level and/or mitigates the failure consequences. This term has the same meaning as 'worth doing'. |
| Evident function | A function whose failure will be naturally detected by the operating crew. |
| Failure consequences | The results and outcomes of a failure, including the type of consequence (environmental, safety, economic) and the severity of the results. |
| Failure mode | A description of a single event or physical condition that prevents the asset from performing its function. |
| Fail-safe | An item that has a protective function is fail-safe if, when it fails, it becomes 'evident' to the operating crew. |

| | |
|---|---|
| FMEA | Failure Modes and Effects Analysis. |
| Function | What the user wants an asset to do. |
| Functional Failure | The inability of an asset to perform a given function. |
| GEVO | The General Electric (GE) term for the GE-Evolution engine. |
| Hidden function | A function whose functional failure will not become evident to the operating crew until a 'multiple failure occurs's, e.g. a seized safety valve. |
| MTBF | Mean Time Between Failures |
| Multiple Failure | A failure of a protective function and its respective protected function. |
| Proactive tasks | Maintenance tasks chosen to proactively prevent failures or mitigate the failure consequences. |
| RCM | Reliability-Centered Maintenance. |
| P-F interval, curve | The P-F curve illustrates the concept of failures exhibiting early warning signs. A detectable *potential* failure condition is designated 'P', the *failure* condition is designated 'F', and the time period between the two is the P-F interval. Refer to figure 2.8. |
| PM | Preventive Maintenance. |
| Run-to-failure | A maintenance strategy that involves no maintenance; the failure is simply accepted. |

| | |
|---|---|
| Safe life | The life before which no failures have occurred. |
| Scheduled Discard | A proactive maintenance task that replaces an item after a set service life. |
| Scheduled Restoration | A proactive maintenance task that overhauls an item after a set service life. |
| Technically Feasible | A task that addresses the identified failure mode. |
| Worth Doing | A task that reduces risk to acceptable level and/or mitigates the failure consequences. |

# Chapter 1

# Introduction

## 1.1 Chapter Overview

Maintenance of an asset is critical to ongoing performance and production. No matter how well suited an asset is to the operation, production targets will never be met if the asset is not maintained to continue performing its function. Conversely, if an asset is over-maintained, faults can be introduced to the system and excess resources consumed with no benefit in functional reliability gained.

This dissertation aims to apply a proven, systematic methodology for developing optimised maintenance tactics for the Rio Tinto Iron Ore Evolution locomotive engine.

## 1.2 Research Aims and Objectives

Currently, RTIO accepts the Original Equipment Manufacturer (OEM) maintenance tactics without a thorough and documented understanding of the value generated by each maintenance task, reducing RTIOs ability to make informed maintenance decisions as the operating context changes. The literature reviewed in section 2.2 reveals an absence of academic literature covering the analysis of locomotive diesel engine maintenance tactics in the operating context of a hot, semi-arid mining environment, indicating that the project can contribute new knowledge in this area.

The knowledge that this project aims to establish is whether RTIO's current Evolution locomotive engine maintenance is optimised for the present operating context as well as the failure modes and risk mitigated by each maintenance task. Underpinning the development of this knowledge are the following research objectives:

1. If the maintenance is not optimised, evaluate and identify areas of excess maintenance, inadequate maintenance and recurring failure modes that are not appropriately addressed by a maintenance task.
2. Research and document failure modes, failure effects and failure consequences to ensure the analysis is thorough and complete. Based on this data, determine tasks that are 'technically feasible' and 'worth doing' in order to address any identified maintenance shortcomings. Identify and document maintenance tasks that may be undertaken informally or not documented in current work management practices.
3. Evaluate the applicability of alternative maintenance and condition monitoring tasks to the asset to improve productivity.
4. Develop knowledge of component failure mode service life characteristics (using the Weibull distribution).
5. Assess engine subsystem performance in terms of maintenance spend, corrective maintenance requirements, production delays and health, safety and environmental risk.
6. Define the operating context of the locomotive engine.

## 1.3 Project Context and Justification

RTIO's Pilbara railroad operation is unique when compared to General Electric Transportation Systems' (GETS) largest customers, the North American Class 1 railroads. This has led to the concern that the standard maintenance tactics recommended by GETS (and currently employed by RTIO) are not optimised for RTIO.

Section 2.4.4 discusses the applicability of the RCM methodology. This project satisfies the criteria, as the locomotive engine is a complex machine subject to an unrefined maintenance regime recommended by the OEM (GETS) and is *operating in a unique and complex environment.*

The following discussion points support the claim that RTIO's Pilbara railroad operation is unique when compared to the majority of North American railroads.

- Production supply chain pressure. J McArthur (2014, pers. comm., 6 March) advises that the RTIO railroad is part of an optimised supply chain and delays in the rail network directly cause lost production, which is critical in a continuous operation. By contrast, general freight railroads (such as the North American Class 1 railroads) have a variety of independent customers with differing business objectives so delays due to equipment failure do not carry the same consequences.

  C Wakeling (2014, pers. comm., 7 March) supports this view. The RTIO network measures derailment cost in the order of $M/hr. Accordingly, delay reduction is the primary focus while general freight railroads have slimmer margins and cost reduction is the primary focus.

- Maintenance depot location. North American railroads utilise maintenance depots at strategic locations on the track network. RTIO only has maintenance depots located on the coast, near the port. This increases the criticality of locomotive failure due to reduced opportunity of mainline locomotive replacement (McArthur, J 2014, pers. comm. 6 March).

  C Wakeling (2014, pers. comm., 7 March) provides a different perspective, believing that it is easier to maintain assets on the RTIO network. RTIO assets always need to travel past a maintenance depot on their journey, while other railroads may not see a particular rolling stock asset travel via a maintenance depot for long periods of time if the asset is 'locked' in traffic travelling a certain part of the network. The asset may be hundreds of kilometres from the nearest depot.

- Climate. RTIO Evolution locomotives feature an oversized radiator to cope with the extreme temperatures encountered. The locomotives are operating on the edge of design limits for heat, but are not concerned with extreme cold and wet weather seen in North American fleets (Wakeling, C 2014, pers. comm., 7 March).

- Track profile. C Wakeling (2014, pers. comm., 7 March) and J McArthur (2014, pers. comm., 6 March) agree that most other railway track profiles are gently undulating with short, steep inclines, requiring maximum locomotive power for short periods of time. The RTIO network has long, gradual inclines that require maximum power. The long periods of heavy loading naturally induces higher levels of wear and tear on the power plant. J McArthur (2014, pers. comm., 6 March) notes that the locomotive is likely to spend in the order of 20% more time producing full power, and the duration of each full power event is much longer. Locomotives are also rotated through positions as ‘banker’ locomotives with the sole purpose of pushing fully-laden ore trains up steep grades out of the mines. While in this position, the locomotive spends all of its time producing full power.

## 1.4 Project Scope

The project scope includes a Reliability-Centered Maintenance analysis of the components physically attached to the mainframe and associated engine systems located in the engine cab that perform a function fundamental to the generation of mechanical power. The timeframe of the project has permitted analysis of the fuel system, combustion air system and the power assemblies (further detail on the system components and boundaries is included in section 3.4 and appendix C).

The implementation of the maintenance recommendations is excluded from the project scope, although it is an essential step to be carried out following the project completion.

## 1.5 System Overview

The engine system is defined as the assembly of eight engine subsystems. The subsystems are detailed in section 3.4 while an overview is provided below:

- Bottom end
- Fuel system
- Engine sensors
- Long power assembly
- Lubricating oil system

- Cooling system
- Combustion air system
- Exhaust air system

## 1.6 Chapter Summary

Chapter one has documented the fundamental research aims, context and scope.

The following chapters lay the foundation for the development of the research goals and the methodology to be employed throughout the analysis.

# Chapter 2

# Literature Review

## 2.1 Chapter Overview

This literature review aims to:

- Identify literature that will inform the project of the research need and the knowledge that this research project can contribute to the academic body of knowledge.
- Assess and establish the suitability of RCM to this project.
- Identify the methodology and requirements for an RCM analysis.
- Review examples of RCM applied to diesel engines in locomotive applications or hot climates in order to identify any existing knowledge gaps.
- Identify diesel engine condition monitoring tools that could be applied to RTIO's GEVO locomotive engine.
- Assess the suitability of reliability modelling for engine failures, and identify applicable methodology.
- Build a foundational knowledge of common engine component failure modes.
- Identify legislation and regulatory requirements pertaining to locomotive engine maintenance.

## 2.2 Previous heavy diesel engine maintenance research studies

The author has found a large amount of research literature produced on the topic of diesel engine maintenance condition monitoring development (including Lowe (2013), Gu & Yang (2007) and Elamin, Gu & Ball (2010)) and diesel engine design (such as Mollenhauer & Tschke (2010), Liu, Huang, Miao & Zuo (2007) and Arcidiacono & Campatelli (2004)), but very little literature discussing the optimisation of the maintenance regime applied to an active asset.

The literature relating to diesel engine maintenance includes the following:

- Milkie & Perakis (2004) discuss the optimisation of diesel engine maintenance overhauls using Weibull modelling of engine failure events (not specific failure modes); however, this is focussing on only the overhaul aspect of engine maintenance, not the ongoing maintenance and purpose for each maintenance task.
- Youngk (2000) investigates the effect of oil drain intervals on engine reliability; again, this is only one aspect of engine maintenance.
- Procaccia, Lannoy & Clarotti (1997) applies statistical theory to determine the optimum lifespan of diesel engine cylinder liners.

The articles referenced above are in the same field as this research project, but only focus on one specific part of the engine maintenance regime. It would appear that while work very similar to this project must have been completed previously for maintenance regimes to exist, it has not been documented in any body of academic literature.

Even if similar work from a different diesel engine application had been found in the literature review, Moubray (2001, pg. 28,79) identifies that the operating context of an asset forms the foundation for the maintenance tactic development and that identical assets in different operations will require unique maintenance tactics. Fundamentally, this concept drives the project research aims, in that the RTIO Pilbara operation is unique (as established in section 1.3), requiring unique maintenance tactics. Research on the maintenance tactics applied to the Evolution locomotive operating in hot, semi-arid mining operations has not been conducted or documented, creating an opportunity for this project to contribute new knowledge to the body of academic literature.

## 2.3 Suitability of the Reliability-Centered Maintenance Methodology

Rausand (1998) writes that after development in the aviation industry, RCM was adapted to a variety of high risk industries including nuclear energy, offshore oil and gas, and military forces. Additionally, the article notes that the RCM concept has been described in several reports, textbooks and standards, both civilian and military. The article presents RCM as a philosophy for maintenance tactic analysis and development of any equipment, and this is supported by Moubray (2001, pg. 1), Netherton (2002), Gabbar, Yamashita, Suzuki & Shimada (2003) and Standards Australia (2011).

Technical groups (SAE, American Society of Materials (ASM), International Electrotechnical Commission (IEC)) and Standards organisations (Australian Standards) have published descriptions and standards for RCM (Netherton 2002) (Standards Australia 2011), supporting the idea that RCM has gained a reputation as an effective and robust methodology across a wide variety of industries. Netherton (2002) further supports this idea and states that RCM is used around the world in almost every industry, and is a "formidably powerful tool".

Specific examples of academic research papers detailing industry application of RCM include:

- Large scale railway networks (Carretero, Prez, Garca-Carballeira, Caldern, Fernndez, Garca, Lozano, Cardona, Cotaina & Prete 2003)
- Power distribution networks (Bertling, Allan & Eriksson 2005)
- Steel manufacturing (Deshpande & Modak 2002)
- Water and utilities (Fynn, Basson, Sinkoff, Moubray & Nadeau 2007)
- Nuclear (Deshpande & Modak 2002b, pg. 3) (Chen & Zhu 2008)
- Space exploration (NASA space shuttle) (Hauge, Stevens, Loomis Jr & Ghose 2000)

The author could not find examples of academically published RCM analyses of heavy-haul diesel locomotive engines, or heavy diesel engines in other applications.

## 2.4 Reliability-Centered Maintenance (RCM)

### 2.4.1 Inception

The RCM process was first documented by F. S. Nowlan and H. S. Heap of United Airlines in 1978 (Nowlan & Heap 1978, pg. vii) for the US Department of Defence. It is considered a seminal work that documented state-of-the-art maintenance in the aviation industry at that time (Netherton 2002). In the 1980's, John Moubray and associates were able to take this maintenance approach and apply it to other industries, culminating in RCMII, which employed the same philosophy as RCM, but treated environmental risks with much more importance (Moubray 2001) (Netherton 2002).

The success of RCM and RCMII led to a number of maintenance programmes being developed and called 'RCM' that did not strictly follow the philosophy proposed by Nowlan and Heap. Industries embarking on an RCM program could not be assured of the validity of a program being offered by a consultant. To counter this problem, the Society of Automotive Engineers (SAE) standards JA1011 and JA were published in 1999, not to provide an RCM methodology, but to provide a standard against which to assess whether a commercial maintenance program is RCM-based or not (Moubray 2001, pg. 326) (Netherton 2002).

### 2.4.2 RCM Definition

Moubray (2001) defines Reliability-centered Maintenance as *"a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context"*. Standards Australia (2011) introduces RCM as "*... a method to identify and select failure management policies to efficiently and effectively achieve the required safety, availability and economy of operation*". Rausand (1998) quotes the Electric Power Research Institute (EPRI) definition: "*a systematic consideration of system functions, the way functions can fail, and a priority-based* *consideration of safety and economics that identifies applicable and effective PM tasks*". Three ideas link the above definitions:

- RCM is a systematic methodology rather than a set of instructions.
- The equipment has performance standards, operating requirements and an operating context. The results of the analysis will be determined by these unique criteria.
- The methodology focusses on maintaining functions rather than the equipment itself (Rausand 1998).

### 2.4.3 RCM Objectives

Standards Australia (2011, pg. 13 - 15) and Moubray (2001, pg. 18, 308-317) identifies the following objectives and benefits of an RCM analysis:

- Develop maintenance schedules, involving the following sub-objectives:
  - Select more appropriate maintenance activities to lift the equipment reliability.
  - Reduce costs and increase availability by eliminating unnecessary maintenance tasks and optimising preventive maintenance tasks.
  - Identify equipment deficiencies that require redesign.
  - Develop maintenance documentation to satisfy future maintenance audits.
  - Development of a knowledge database that provides a clear demonstration of the purpose of all maintenance tasks.
  - Provide a foundation for maintenance program revision through time.
- Create asset operating procedures.
- Reduce safety and environmental risk.
- Extend equipment life.
- Imbue a higher level of plant and machinery knowledge to the company.

### 2.4.4 When to perform an RCM Analysis

RCM is well-suited to applications involving complex machinery that is in service and has a generic maintenance regime (Moubray 2001, pg. 79), but is operating in a unique and demanding context that may have significant safety and environmental risks (Deshpande & Modak 2002b, pg. 33).

Standards Australia (2011, pg. 30) indicates that an RCM analysis performed during design will offer the best outcomes, as it can influence design decisions. Netherton (2002) provides an example of designing a casing to fail by ductile deformation as opposed to brittle failure, but goes on to say that RCM was developed for those responsible for maintaining the asset, not the design engineer. Moubray (2001, pg. 312) agrees with the Australian Standard; however, Moubray (2001, pg. 77-79) and Rausand (1998) assert that equipment manufacturers and third parties are rarely in a position to provide a quality FMEA for a RCM-based maintenance regime, for the following reasons:

- Most manufacturers do not operate and maintain their equipment, removing a fundamental information source for performing an RCM analysis.
- Manufacturers may be aware of failures but usually do not have access to operational information to understand the failure modes.
- The manufacturer often does not have access to operating context, performance standards and failure consequences, or it may not be viable to manufacture items to suit these parameters in a production line scenario.
- Designers may be less inclined to admit that the equipment can fail.
- Recommendations by the manufacturer for scheduled replacement will have a conflict of interest as the manufacturer will benefit from spare parts sales.
- Legal liability concerns may influence the manufacturer to prescribe more maintenance than is necessary.

## 2.5 Reliability-Centered Maintenance Methodology

### 2.5.1 Planning and Preparation

The literature reviewed by the author recommends that the following points are considered and attended to prior to attempting an RCM:

1. Establish participant prior experience and knowledge. The following knowledge base underpins a successful RCM analysis, and if not available needs to be developed:

    - RCM experience
    - Knowledge of equipment and operational context
    - Knowledge of equipment condition, failures modes and effects
    - Access to relevant safety and environmental legislation or regulations
    - Understanding of maintenance practicalities, processes and costs

    (Standards Australia 2011, pg. 17)

    Moubray (2001, pg. 267) agrees with this concept, and advises that the RCM group should include five or six participants, including operators, tradesmen, their respective front-line supervisors, engineers and, where appropriate, external technical specialist advisors. Particularly for new assets, Moubray (2001, pg. 78) believes that the manufacturer's field service technicians can be of great value, when coupled with the day-to-day maintainers and operators who understand the operating context and failure effects.

    The facilitator has the most significant effect on the quality of the analysis. Moubray (2001, pg. 269-277) recommends the facilitator is a technical and methodical person with good people skills. Further, they should understand the asset to be analysed, but not be a subject matter expert. The facilitator must be competent in the following areas:

    - Applying RCM logic
    - Directing and managing the analysis
    - Conducting meetings

- Time management
- Administration, logistics and communication

2. Establish objectives. Netherton (2002) explains that each RCM will have different priorities and objectives, as discussed in section 2.4.3.

3. Define the level of analysis. A high-level analysis may miss important failure modes and detail, while a low-level analysis may become overwhelming (Rausand 1998) (Netherton 2002). Moubray (2001, pg. 80-89) advises that the FMEA analysis level can be adjusted as new information comes to light during the RCM analysis. If there are less than six failure modes per sub-system, the analyst should consider incorporating the failure modes into a higher level system. If there are greater than 10 failure modes per sub-system, it may be worth analysing some of the assemblies separately.

   Smith & Hinchcliffe (2003, pg. 75) broadly defines the levels of analysis as:

   - Part - the smallest component that can be disassembled from the equipment assembly without damage.
   - Component - an assembly of parts that perform a significant function.
   - System - a set of components that provide a fundamental function for the plant operation.
   - Plant - An assembly of equipment that takes raw input materials and processes them into output products.

   Smith & Hinchcliffe (2003, pg. 75-76) recommends that the RCM is performed at a system level, based on the following reasons:

   - Equipment is often designed and built at the system level, so the RCM is congruent with the plant construction, enabling boundaries to be easily defined.
   - Analysis at the component level can mask the true impact of a failure, as the RCM is focussed on component failures and may miss the big picture.
   - Analysis at the highest plant level may include a large number of functions. This can result in the analysis becoming large, cumbersome and confusing.

4. Define the asset/system boundaries. Netherton (2002) and Rausand (1998) agree that the analysis level, system boundaries and analysis approach to interfaces

need to be documented during the planning stage (Standards Australia 2011, pg. 18).

Smith & Hinchcliffe (2003, pg. 82-86) emphasises that boundaries must be defined and documented precisely, and, if done well, generates the following benefits:

- Where system overlap occurs and no clear boundary exists, a precise definition prevents the same work being completed twice when analysing the interfacing systems.
- The inputs and outputs are clearly understood, helping to clarify the system functions.

Smith & Hinchcliffe (2003, pg. 82-86) goes on to discuss a pragmatic approach to defining boundaries. He does not give a set of rules, but provides some specific examples that indicate the boundaries should be set to group items that support a system function. One such example is that of the lubrication system - while a component may include lubrication, the lubrication system itself may service many components. As such, the lubrication functions in each component should be grouped and analysed as part of the lubrication system. These system groupings, and any special cases, must be documented precisely. Smith suggests the format in figures 2.1 and 2.2.

5. Prioritise assets/systems. Rausand (1998) and Netherton (2002) indicate that this is a controversial step; some RCM methodologies argue that this is not important and wastes time, as every asset requires analysis. Proponents of prioritisation and justification believe that some assets do not justify analysis, and prioritisation focusses the RCM resources appropriately. Moubray (2001, pg. 16) agrees that assets should be prioritised and Standards Australia (2011, pg. 15-16) advises that the analyst needs to identify the systems that will benefit most from RCM and produce a listing of items ranked by criticality and priority. Assets can be assessed against the following criteria:

   - Availability/reliability performance
   - Safety incidents
   - Maintenance backlog
   - Maintenance costs/efficiency
   - Proportion of corrective work to preventive work

**RCM - Systems Analysis**

| | | | |
|---|---|---|---|
| **Step 2-1:** | **System Boundary Definition** | **Plant ID:** | |
| **Information:** | **Boundary Overview** | **System ID** | 00651-020304 |
| **Plant:** | VKF HPA Auxiliary Plant | **Rev No:** | 0 |
| **System:** | JM3 Pumping System | **Date:** | 2/20/98 |
| **Subsystem:** | C92 Compressor System | | |
| **Analysts:** | Ed Ivey, Brian Shields, Brown Limbaugh, Ronnie Skipworth, Glenn Hinchcliffe (facilitator) | | |

**Major Equipment Included:**



GE 1250 Hp 6900V Induction Motor
Ingersal- Rand 3 Stage Centrifugal Compressor
Coupling
Lube Oil Pump
Pre-Lube Pump/Motor
Lube Oil Cooler
Inlet Air Filter
V921,V928, V925, Vent Valve

**Primary Physical Boundaries**

**Start with:**

Air from atmosphere entering into the filter

**Terminate with:**

38 PSIG air at approximately 100F on outlet side of V925

Vent excess air to atmosphere through outlet of vent line



**Caveats:**

Did not include any electrical supply breaker, starter, or cables in this analysis

| | | |
|---|---|---|
| **System:** | JM3 Pumping System | Sunday, June 08, 2003 |
| **Subsystem:** | C92 Compressor System | Page 1 of 1 |

**Step 2-1 Boundary Overview**
**JMS Software**

Figure 2.1: Boundary Overview (Smith & Hinchcliffe 2003, pg. 85)

**RCM - Systems Analysis**

| | | | |
|---|---|---|---|
| **Step 2-2:** | **System Boundary Definition** | **Plant ID:** | |
| **Information:** | **Boundary Details** | **System ID** | 00651-020304 |
| **Plant:** | VKF HPA Auxiliary Plant | **Rev No:** | 0 |
| **System:** | JM3 Pumping System | **Date:** | 2/20/98 |
| **Subsystem:** | C92 Compressor System | | |
| **Analysts:** | Ed Ivey, Brian Shields, Brown Limbaugh, Ronnie Skipworth, Glenn Hinchcliffe (facilitator) | | |

| Type | Bounding System | Interface Location | Reference Drawing |
|---|---|---|---|
| OUT (Air) | 93A/B Compressor | Down stream side of V925 | 20-00054.18 |
| IN (Air) | Atmosphere | Up stream side of inlet filter | 20-00054.18 |
| OUT (Air) | Atmosphere | Outlet of ducting | 20-00054.18 |



| | | |
|---|---|---|
| **System:** | JM3 Pumping System | Sunday, June 08, 2003 |
| **Subsystem:** | C92 Compressor System | Page 1 of 1 |

**Step 2-2 Boundary Details**
**JMS Software**

Figure 2.2: Boundary Definition (Smith & Hinchcliffe 2003, pg. 86)

- Maintenance technology used

Smith & Hinchcliffe (2003, pg. 76-79) is a strong advocate of prioritising assets, advising that some equipment does not justify resource allocation. The Pareto Principle (80 percent of the effects are the result of 20 percent of the causes or actions) is introduced as a practical tool to determine the assets which are likely to provide the best return on investment from RCM analysis resources.

A Pareto analysis builds a histogram based on a suite of assets and a performance parameter, which are then sorted from the largest performance parameter result to the smallest. Naturally, the assets that display the worst performance are prioritised first, as the Pareto Principle indicates that these assets will require the least effort to make the biggest improvement in performance. An example chart is provided in figure 2.3.

Smith & Hinchcliffe (2003, pg. 77) advises that the analysis is kept simple. The following data should be easily obtained and is sufficient to provide direction to the analyst:

- Corrective maintenance expenditure (2 year period)
- Count of corrective maintenance events (2 year period)


Figure 2.3: Pareto Chart(Smith & Hinchcliffe 2003, pg. 79)

- Downtime (2 year period)

As discussed earlier, Standards Australia (2011, pg. 15-16) indicates that plant should be assessed against reliability and availability performance. Besnard, Fischer & Bertling (2010) describes reliability performance using downtime and number of failures, which is similar to the criteria set out by Smith & Hinchcliffe (2003, pg. 77).

6. Define the operating context. The operating context is defined during RCM preparation, and is to be documented for use with the analysis and as evidence afterwards (Standards Australia 2011, pg. 17-18). Standards Australia (2011, pg. 17-18), Moubray (2001, pg. 28-35) and Society of Automotive Engineers (2002) indicate that the operating context documents general knowledge of:

- How the equipment is operated, operating parameters and demand/duty cycle.
  - Is the process a batch or flow process, and what is the volume of work-in-progress (WIP)? Batch processes may mitigate some of the failure effects, but a flow process may shut down the entire plant when one piece of equipment fails.
  - Equipment redundancy.
  - Operating hours - shift or continuous.
- Climate and environmental considerations.

- Failure rates, time-to-repair and spare part lead times.
- Health, safety, environmental and quality standards.
- Equipment/system interfaces, and how the analysis will deal with these.
- Economic climate, market demand and raw material supply.

7. Gather information and data. Information to be collated during the preparation stage will include:

   - Operating procedures
   - Equipment/System Bill Of Materials (BOM)
   - Applicable novel maintenance techniques
   - Methodologies for calculating potential to functional failure intervals and task intervals
   - Appropriate reliability analyses
   - Relevant regulations and legislation
   - Safety assessments, incident, accident and failure reports
   - Technical manuals, schematics, assembly drawings and manufacturer's handbooks
   - Existing maintenance procedures and preventive maintenance tasks
   - Spare parts usage rates

   (Standards Australia 2011, pg. 18-19)

   Standards Australia (2011, pg. 16) advises that maintenance history data sources alone are insufficient for the RCM analysis and can even be misleading. Moubray (2001, pg. 250-255) supports this strongly. Data needs to be augmented by evidence from maintenance personnel and equipment inspection.

### 2.5.2 Introduction to the Seven Questions of RCM

Moubray (2001, pg. 7-16, 210-211), Netherton (2002) and Society of Automotive Engineers (2009) explicitly deal with the seven questions in discrete steps:

1. What are the asset functions?

2. How does it fail to fulfil the asset functions?
3. What is the physical condition or event that causes the function to fail?
4. What are the effects of the failure?
5. What are the consequences of the failure?
6. Can a proactive action be taken to prevent the failure?
7. If it is not possible to proactively prevent the failure, what can be done?

Rausand (1998) and Standards Australia (2011) give a somewhat implicit treatment, grouping a number of the questions together into a single step. This project will deal with each question separately as proposed by Moubray (2001), Society of Automotive Engineers (2009) and Netherton (2002).

### 2.5.3 Function Definition

**What are the functions and associated performance standards of the asset in its present operating context?**

Moubray (2001, pg. 8) and Society of Automotive Engineers (2002) define primary and secondary functions. Primary functions are the reason for the asset's existence, i.e. the reason it was purchased. Secondary functions address the environment, safety and human interface factors. Secondary functions may be more critical than primary functions. Additionally, functions can be 'hidden', meaning that the function (and failure) is not apparent under normal operation (e.g. seizure of a safety valve).

Function definition will take 30% of the time for the entire RCM (Moubray 2001, pg. 8) and (Netherton 2002). This is consistent with the RCM philosophy of focussing on equipment functions, not equipment *per se* (Deshpande & Modak 2002b).

Standards Australia (2011, pg. 20-21), Moubray (2001, pg. 22-44), Society of Automotive Engineers (2002) and Netherton (2002) detail the following salient points:

- The structure of a function statement includes a verb, object and performance standard. The operating context of the function needs to be included, but may be included as a separate text description where applicable.

- A quantitative performance standard should be specified (where applicable) or an absolute standard inferred.
- Secondary functions need to be considered (e.g. lubricating oil containment).
- Protective functions must identify when the protection would apply.

### 2.5.4 Functional Failure Definition

**In what ways does the asset fail to fulfil its functions?**

Failed states are described by Moubray (2001, pg. 46-47) as *functional failures* because they are defined by an inability to fulfil a certain function to the required standard. Standards Australia (2011, pg. 21-22) categorises functional failures as:

- Complete functional loss
- Partial loss of function
- Intermittent functional loss
- Functioning at the wrong time (e.g. a low oil pressure alarm giving false alarms)

Rausand (1998) adds that the functional failures need to be classified into sudden or gradual failures, but does not provide a strong reason for this classification. Standards Australia (2011), Moubray (2001) and Netherton (2002) do not provide any support for this and indicate that sudden or gradual failures are dealt with in Questions 3 and 4, the failure modes and effects analysis.

Netherton (2002) writes that functional failures are simple and precise to write if the functions have been well defined initially.

### 2.5.5 Failure mode definition

**What causes each functional failure?**

A *Failure mode* is defined as the physical condition or event that causes the functional failure, under 'reasonably likely' conditions. The term 'reasonably likely' should be interpreted with respect to the operating context, as rare failure modes that have catastrophic consequences must be addressed.

A quality failure mode description will include an object and a verb, which is an identification of the physical item and the mechanism by which the item failed.

The failure mode should be consistent with the failure management strategies available and provide enough information to select a failure management strategy. As an example, a slurry pump failure mode may be described as 'impeller worn out of adjustment', which can be managed by periodic inspection and adjustment. In this instance there is little to be gained by specifying the failure mode at the impeller metallurgical composition level, because it is the impeller clearance that will be maintained.

(Moubray 2001, pg. 54) (Standards Australia 2011, pg. 21-22) (Society of Automotive Engineers 2009) (Society of Automotive Engineers 2002)

Other considerations when determining failure modes should be:

- Failure modes that have occurred previously, and those being prevented by current preventive maintenance, should be included.
- Opportunities for operator error causing failure.
- Environmentally-induced failure modes.
- Known design deficiencies.
- Human error. Standards Australia (2011, pg. 22) suggests that human error may or may not be included depending on resources and organisational context. These modes may be listed for completeness but not analysed further. Moubray (2001, pg. 70) indicates that if the error is thought to be reasonably likely, then it should be included.

Moubray (2001, pg. 77-80,266-267) identifies that tradesmen, frontline supervisors and OEM field service technicians are key sources of information for failure modes and failure effects. (Failure effects are described in Question 4.)

A thorough assessment of failure modes forms the basis of a proactive maintenance effort; it is considering all of the things that could potentially go wrong before they happen (or happen a second time in some cases), such that appropriate failure management policies can be implemented (Moubray 2001, pg. 55).

Rausand (1998) defines failure modes as "the manner by which a failure is observed, and is defined as non-fulfilment of one of the functions". Netherton (2002) identifies this definition as the traditional design FMEA failure mode definition. This definition will not be pursued further in this project.

### 2.5.6 Failure effects evaluation

**What happens when each failure occurs?**

*Failure effects* describe the events that follow a failure mode. It is important to differentiate between effects (Question 4) and consequences (Question 5). Failure effects describe what happens when the failure occurs and the consequences describe how the failure matters (safety, operational, etc.) and the severity of the failure (Moubray 2001, pg. 73).

The failure effect describes the 'reasonably likely' most severe effects of failure when no action is taken to detect or prevent the failure (Standards Australia 2011, pg. 22). Netherton (2002) agrees and adds that the 'no action taken' restriction enables the true consequence of failure and benefit of maintenance tasks to be assessed.

Netherton (2002) and Standards Australia (2011, pg. 22) note that a quality failure description includes the information required to thoroughly assess the consequences (Question 5). Moubray (2001, pg. 73 - 77) and Society of Automotive Engineers (2002) express similar ideas and discuss the items that a quality failure effect description will include:

- Evidence of failure - alarms and physical effects (smoke, product leakage, etc.)
- Safety and environmental effects
- Operational and production effects
- Physical (secondary) damage caused
- How the failure is repaired

The level of detail of the effects need to be explored and documented at the subsystem, system and the overarching plant level, so that the failure effects are viewed holistically and are comparable with each other (Standards Australia 2011, pg. 22).

### 2.5.7 Failure consequence evaluation

**In what way does each failure matter?**

Assessing the *failure consequences* categorises and evaluates risk. Question 5 works with Question 6 (What can be done to predict or prevent failure?) and 7 (What should be done if a suitable maintenance task cannot be found?) to assess the proposed maintenance tasks against the 'technically feasible' and 'worth doing' criteria. Evaluating the risk associated with a failure determines the resources allocated to a task, as it determines whether a task is 'worth doing'. This concept counters the idea that 'all failures must be prevented' and is a key concept in the RCM methodology.

Moubray (2001, pg. 91) classifies failure consequences into four broad consequence categories (RCM2 decision diagram, figure 2.4):

- Safety and environmental
- Operational
- Non-operational
- Hidden failures, which are distinct from evident failures and require special treatment

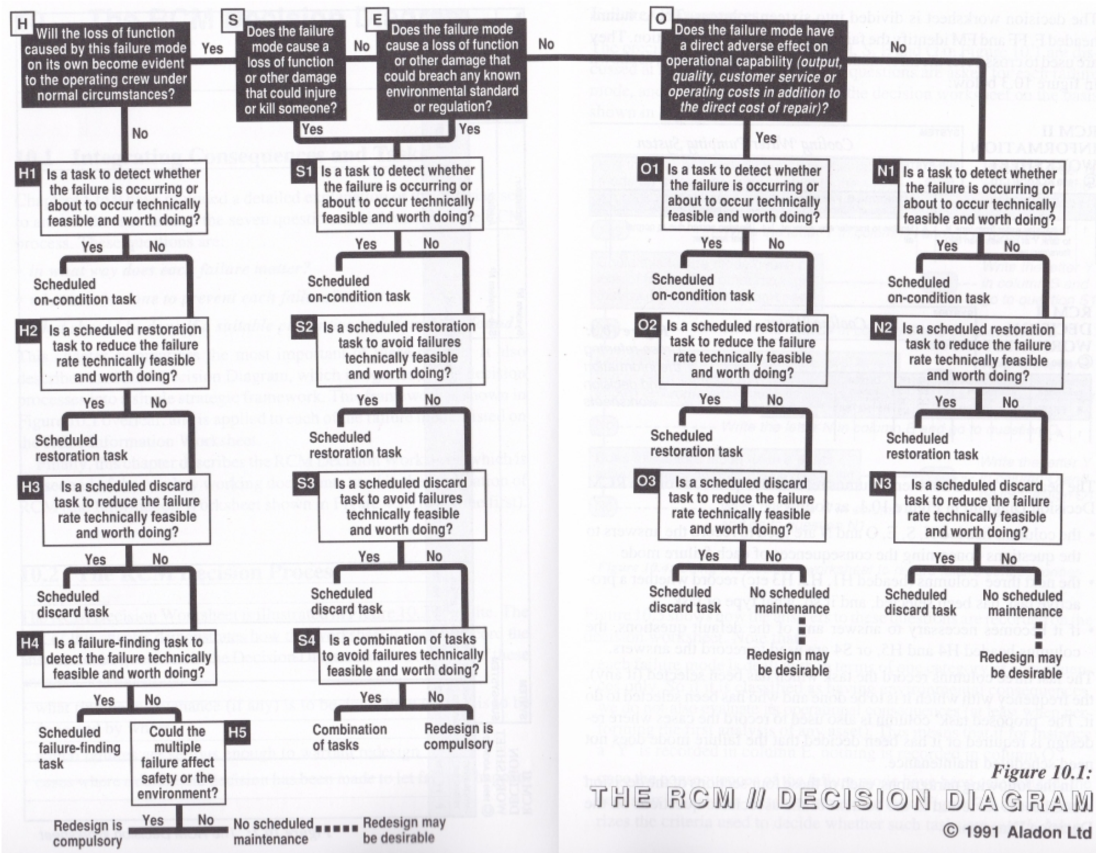



Figure 2.4: RCM2 Decision Diagram (Moubray 2001, pg. 200-201)

Netherton (2002) classifies consequences in the same manner as Moubray (2001), except that environmental consequences are a separate category from safety.

Referring to figure 2.5, Standards Australia (2011, pg. 25-26) classifies the failures into the following categories:

- Evident, safety and environmental
- Evident, operational/economic
- Hidden, safety and environmental
- Hidden, operational/economic

**Evident Failures** are defined by their noticeable effects, which may be as simple as a warning light or as catastrophic as plant process interruption and damage to personnel or the environment. The failure does not have to be evident instantly but it does have to be evident on its own, not requiring another failure, inspection or ‘failure-finding’ activities to be detected (Moubray 2001, pg. 92-93).

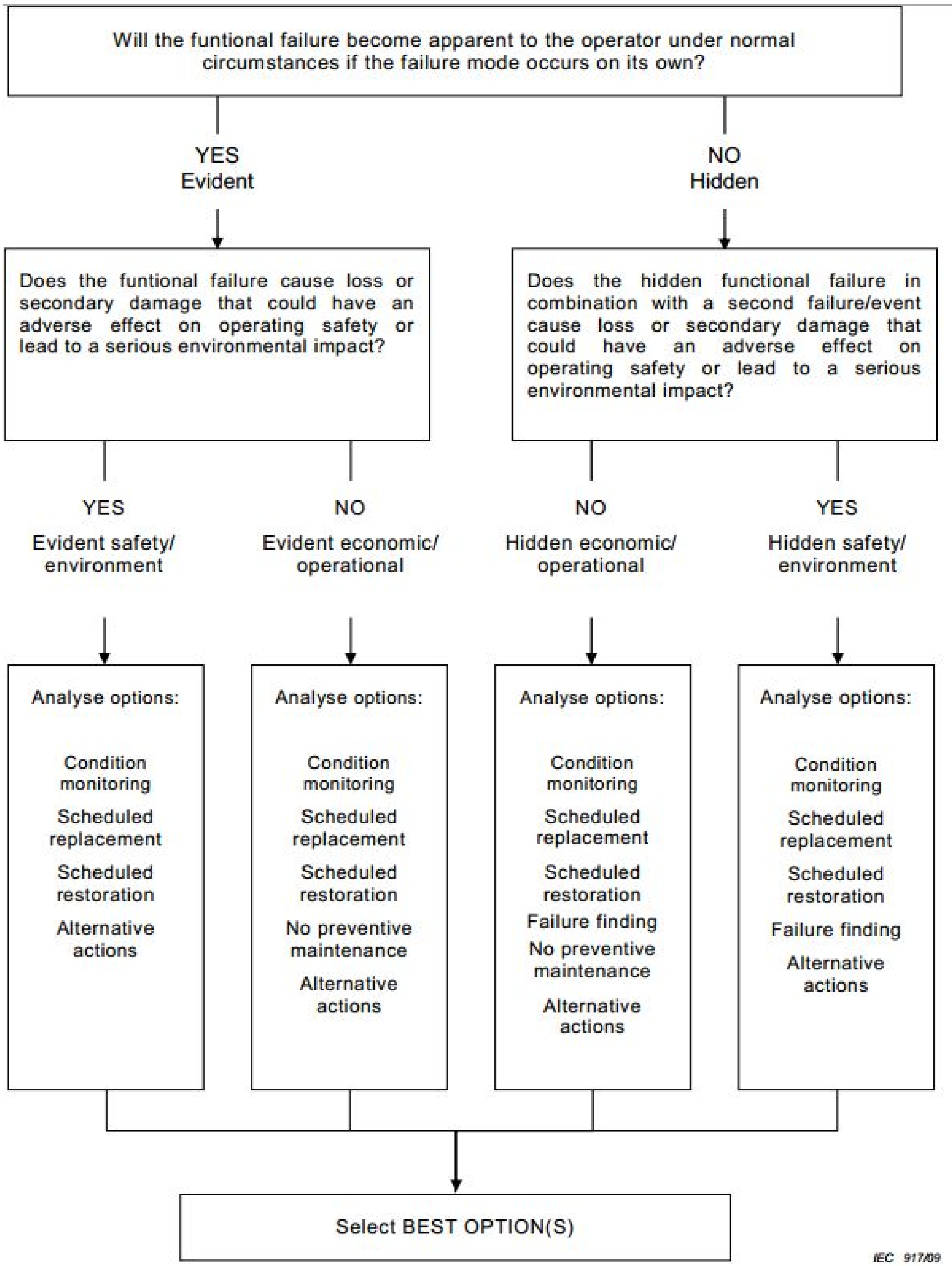



Figure 2.5: AS IEC 60300.3.11 RCM Decision Diagram (Standards Australia 2011, pg. 25)

**Hidden Failures** are the result of protective functions that are not fail-safe. They are not detectable on their own under normal operating circumstances and are defined by a lack of the symptoms seen with evident failures. Their undetected failure may allow a second failure ('multiple failure') to occur, whose consequences are likely to be significant. Hidden failures require a 'failure-finding' activity to discover the fault.

The example provided is that of a stand-by pump. If the shaft bearings seize, the seizure will not be discovered unless the duty pump fails and the stand-by pump is called upon to perform but fails (this would be considered a 'multiple failure'), or unless the stand-by pump is tested.

A maintenance task to prevent failure of the hidden function is considered 'technically feasible' if it reduces the probability of multiple failure to a tolerably low level. It is considered 'worth doing' if the value of the task outweighs the cost of the task.

(Moubray 2001, pg. 92, 114-116) (Society of Automotive Engineers 2002)

**Safety and Environmental Consequences** are failures that cause injury or death to people and failures that breach any local, state or national regulations (Moubray 2001, pg. 94-95). The RCM process does not tolerate inaction on safety or environmental risks and they must be reduced to a tolerably low level. As such, proactive maintenance tasks are only 'worth doing' if they reduce the risk to a tolerably low level (Moubray 2001, pg. 102). It is important to note that secondary damage caused by a failure is sometimes confused with safety consequences, but RCM classifies secondary damage as 'non-operational' consequences (Netherton 2002).

**Operational Consequences** Standards Australia (2011, pg. 26) classifies operational consequences as those that cause a degradation of capability, reduced production, or failure to complete a journey on-time. Netherton (2002) agrees, and emphasises the effect of lost sales on 24-hour production plants. Moubray (2001) notes that the following parameters are affected:

- Total output
- Product quality
- Customer service (particularly in scheduled or time-based products like transport)

- Operating costs (in addition to the cost of repair)

A proactive maintenance task is only 'worth doing' if the cost of the task is less than the economic effects of failure. The economic effects are quantified by how much the failure costs and how often it occurs (Moubray 2001, pg. 105-106). Netherton (2002) believes that indirect operational impacts should be measured. An example is to calculate the redundancy level utilised to support the operation, adding indirect costs. Moubray (2001, pg. 108) urges the team to thoroughly assess whether the task is 'worth doing', in either a formal, quantitative manner or intuitively (as appropriate). Many teams display a tendency to evaluate tasks only against the 'technically feasible' criteria, yielding maintenance programs that cost more than the failures they prevent.

RCM recommends that if a maintenance task, redesign or process change is not 'worth doing' and the failure consequences are tolerable, the best maintenance strategy may be 'Run To Failure'; that is, perform no maintenance and accept the failures (Moubray 2001, pg. 106-107).

**Non-operational consequences** are described by Standards Australia (2011, pg. 26) as 'economic' and defined by Netherton (2002) as any failure that matters because it requires repair but does not affect safety, environment or the operation. Moubray (2001, pg. 109-110) re-emphasises the message that these failures should only be prevented if the cost of maintenance is less than the cost of failure.

Two further points to be considered are:

- Secondary damage should be included in the assessment of failure cost.
- Protected functions, such as a duty pump with a redundant standby, may be classified as a non-operational failure but the implication is that the protective function *must* be maintained as well.

(Moubray 2001, pg. 95-101,110)

The analyst may evaluate risk to determine the severity of consequences and resources available to prevent the failure. This should be performed in a group (Moubray 2001, pg. 101) and can be assisted by using a matrix similar to figure 2.6. The likelihood (left hand column) can be determined quantitatively (reliability data) or qualitatively (engineering judgement), as long as the approach is consistent. The consequence sever-

| Likelihood | Category | Consequence | | | |
|---|---|---|---|---|---|
| | | Catastrophic | Major | Marginal | Minor |
| | | 1 | 2 | 3 | 4 |
| Frequent | A | 1 | 1 | 2 | 2 |
| Likely | B | 1 | 2 | 2 | 3 |
| Occasional | C | 2 | 2 | 3 | 3 |
| Unlikely | D | 2 | 3 | 3 | 3 |
| Remote | E | 3 | 3 | 3 | 3 |

Figure 2.6: AS IEC 60300.3.11 Criticality Determination Matrix (Standards Australia 2011, pg. 39)

ity levels are defined according to the organisation's context. The result of this analysis is a risk ranking for each failure mode. The example in figure 2.6 has three risk values, ranging from one (unacceptable) to three (minor) (Standards Australia 2011, pg. 22-23).

### 2.5.8 Proactive maintenance task selection

**6. What can be done to predict or prevent each failure?**

Question 6 assesses 'proactive' maintenance tasks. Proactive tasks are divided into three categories: scheduled restoration, discard, or on-condition (Moubray 2001, pg. 129).

Standards Australia (2011, pg. 26) recommends that the failure mode characteristics are assessed to determine the maintenance tasks that will be 'technically feasible' for each failure mode. There are six failure patterns (figure 2.7), and the relationship between age and failure risk is a key concept (Moubray 2001, pg. 130) (Society of Automotive Engineers 2002). The analyst is warned not to use plant historical records alone as the basis for this assessment, for the following reasons:

- The complexity of equipment failure can be enormous - a functional failure can be caused by numerous failure modes. Historical data often does not record

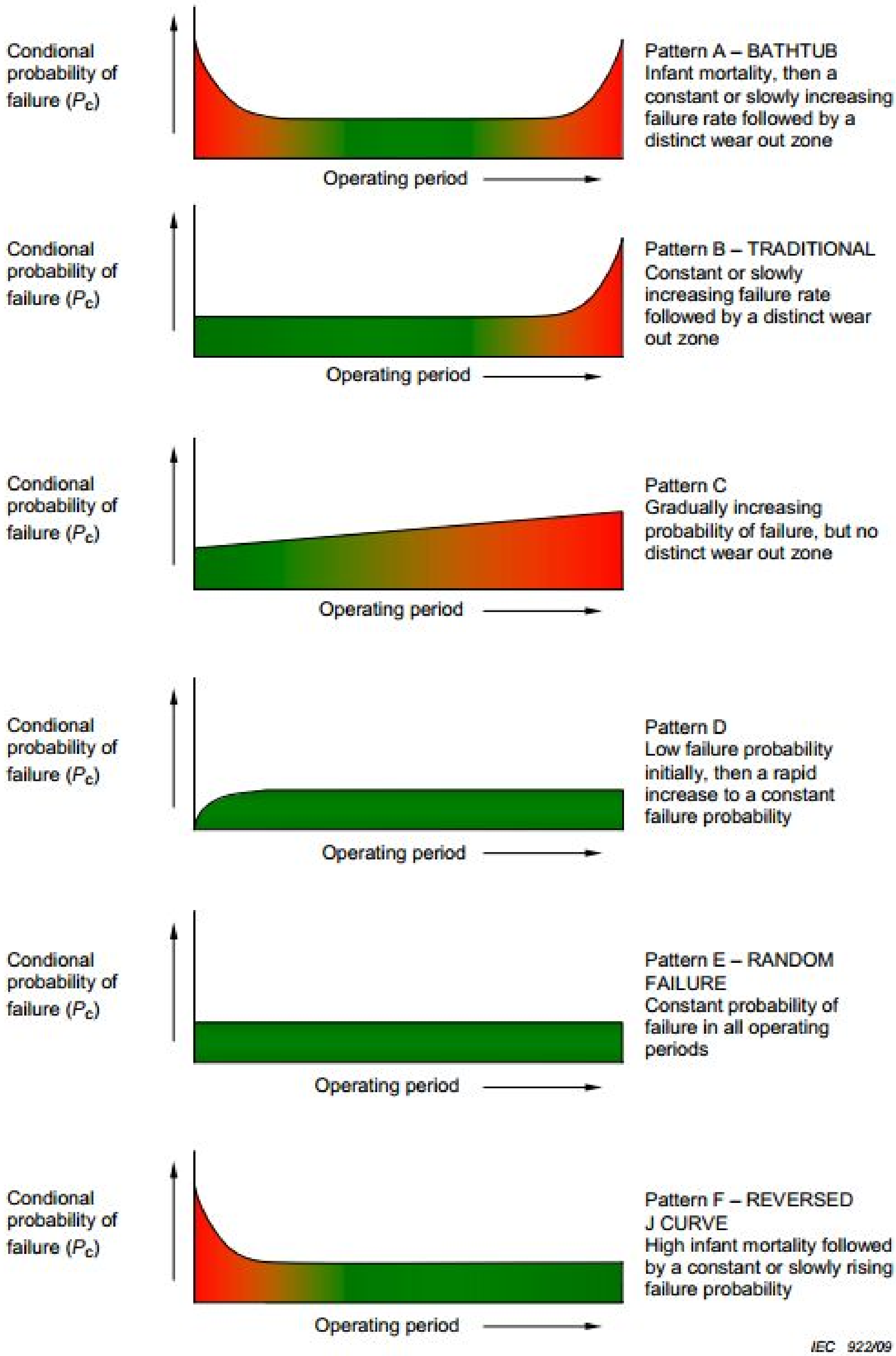



Figure 2.7: AS IEC 60300.3.11 Six Failure Patterns (Standards Australia 2011, pg. 42)

information to this level of detail.

- A plant may only contain a small number of a particular asset type, and these assets may be modified over time. This means there is an insufficient sample size.
- Many plants struggle with consistent and complete reporting, eroding the quality of historical data.
- Maintenance programs are designed to prevent failures, and hence failure data.
- Historical data, by nature, is backward-looking, while RCM strives to be proactive and forward-looking.

Moubray asserts that RCM focusses on the information needed to justify specific decisions, so historical data is to be used but not solely relied upon (Moubray 2001, pg. 250-255).

The failure management policies are detailed below:

- Scheduled Replacement and Scheduled Restoration tasks are defined by maintenance based on time, not condition.

  Restoration is technically feasible when the equipment exhibits a clear wear-out pattern, as described in figure 2.7, and restoration will renew the equipment's resistance to failure. Scheduled replacement and restoration can still be applicable when an item has a steadily increasing failure rate with age and does not affect safety or the environment.

  If the restoration or replacement task is addressing safety related consequences, a conservative interval ('safe life') is chosen to prevent *any* failures but if it is addressing operational effects, the maintenance cost and failure cost will be compared to determine the 'economic' or 'useful' life.

  If quality failure data is available, reliability data analytical techniques such as the Weibull distribution can be used to determine the task interval. Moubray notes that if this data is not available, key items should be subject to 'age exploration' upon entry to service.

  (Standards Australia 2011, pg. 29), (Moubray 2001, pg. 134-140)

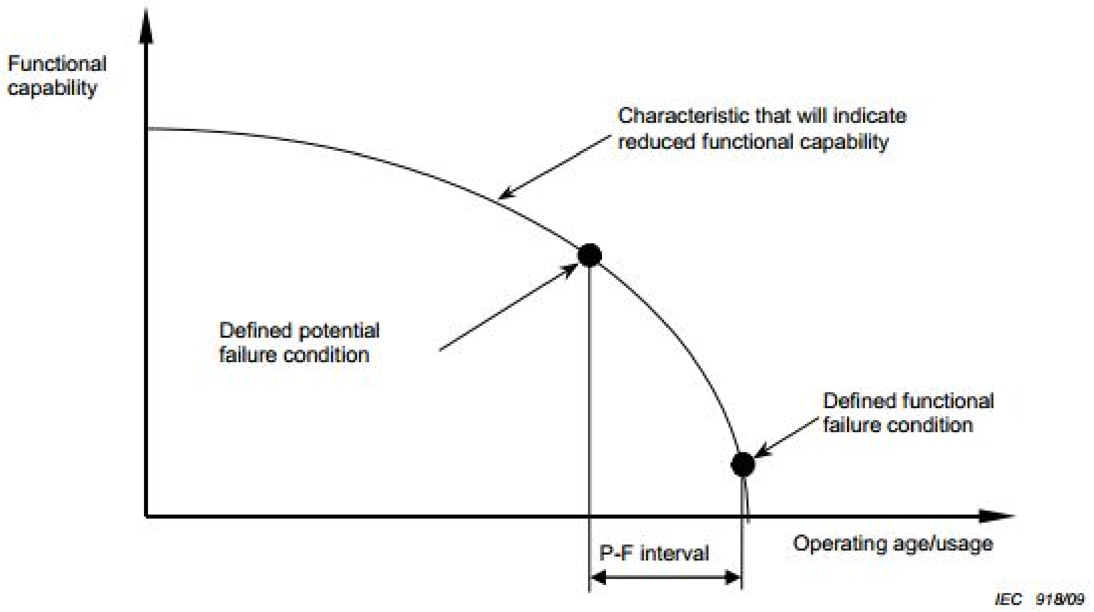



Figure 2.8: AS IEC 60300.3.11 P-F curve (Standards Australia 2011, pg. 28)

- On-condition tasks are performed when a scheduled condition monitoring task indicates that the equipment will fail sometime in the future. Condition monitoring is applied to detect potential failures (P) before they become functional failures (F) (figure 2.8). Potential failures are detectable and measureable. Potential failures display consistent signs of degradation, which may include wear particles, oil consumption, vibration, noise and temperature changes.

  Detecting these early signs of failure gives the maintenance and production departments the opportunity to mitigate, or even eliminate, failure consequences by:

  - Organising materials and labour ahead of time;
  - Arranging the best possible time for equipment outage; and
  - Identifying any other opportune maintenance.

  For a condition monitoring task to be 'technically feasible', the conditions listed must be met:

  - The deterioration can be detected and measured.
  - The inspection interval (if monitoring is not continuous) must be shorter than the P-F interval (refer to figure 2.8).
  - The P-F interval allows enough time to organise corrective maintenance.
  - The failure mode exhibits a relatively stable and predictable P-F interval.

Condition monitoring tasks do not need to be high-tech and some tasks only require the human senses. Moubray (2001, pg. 150)warns that high-tech condition monitoring can be 'spectacularly effective when appropriate, but when they are inappropriate they can be a very expensive... waste of time'.

(Standards Australia 2011, pg. 28-29) (Moubray 2001, pg. 144-150)

### 2.5.9 Default maintenance task selection

**7. What should be done if a suitable proactive task cannot be found?**

Question 7 assesses 'default actions', which can be 'failure-finding', 'run-to-failure', or equipment redesign.

**Failure-finding** tasks evaluate the integrity of a hidden function at scheduled intervals and may take the form of an inspection, partial function test or full function test. Failure-finding tasks are used if proactive maintenance is not sufficient to ensure a tolerable level of risk (which is common for hidden functions). This type of task is generally applied to test hidden redundancy functions (e.g. a backup pump) or protective functions (e.g. a safety relief valve) that are rarely activated.

The task is considered 'technically feasible' if:

- The task is physically able to be done.
- The task does not mean that the system is left unprotected and at risk of failure.
- The calculated failure-finding interval is sensible.

The goal of a failure finding task is to reduce the probability of multiple failure (failure of the protective function and protected function simultaneously) to an acceptable level. If the task is not capable of this, it is not 'worth doing'.

A fundamental consideration when implementing a failure-finding task is the inspection interval. There are a number of ways of determining the scheduled interval, presented by both Moubray (2001, pg. 176-177) and Standards Australia (2011, pg. 40-41). These calculations were not required in this research project; as such, they are not included.

**Run-to-failure** is simply corrective maintenance - no preventive maintenance is applied and the asset is repaired or replaced when failure occurs. It is valid for both hidden and evident failures when:

- There are no environmental or safety consequences resulting from failure.
- There are no preventive tasks that are 'worth doing' to counter the failure; the cost of preventing failure outweighs the cost of the failure.

(Moubray 2001, pg. 187)

**Redesign** is the final default action. It is compulsory for environmental or safety consequences and may be desirable, based on economic cost-benefit, for operational or non-operational consequences.

Redesign is only considered after checking all maintenance options to gain the required performance (Moubray 2001, pg.107). RCM investigates maintenance first because:

- Moubray (2001, pg. 189) makes the point that redesign projects can take six months to three years to implement. During that time, a safety or environmental risk may be active, but the RCM process mandates action. In this instance, Standards Australia (2011, pg. 30) recommends evaluating operational restrictions, temporary modifications or maintenance strategies previously rejected.
- There are often numerous redesign opportunities in a plant and only the most beneficial can be completed (Moubray 2001, pg. 189).

Redesign generates economic benefits when it:

- Reduces failure frequency
- Mitigates or eliminates the failure consequences
- Is cheaper than the current maintenance method

(Moubray 2001, pg. 107)

Redesign may take the form of:

- Changing equipment specifications
- Replacing or substituting the machine or device for a more reliable unit
- Changing the plant process or operating procedure

- Duplicating the equipment or protective functions
- Change the configuration to make a preventive maintenance task cheaper.
- Add another protective device that will make a hidden failure evident
- Training employees.

The cost-benefit of redesign may be difficult to determine, and the following questions are suggested for evaluation:

1. Does the equipment have enough life left to justify the redesign cost?
2. Is the unreliability of the equipment intolerable?
3. Are the failure consequences intolerable?
4. Are the maintenance resources consumed by the asset too high?
5. Will redesign reduce overall costs?
6. Is redesign likely to succeed, given the technology and expertise available?
7. Does a cost-benefit analysis justify the investment?

(Moubray 2001, pg. 188-197)

### 2.5.10 Common Mistakes

Moubray (2001, pg. 286-290) identifies the following mistakes when applying RCM:

- The analysis is carried out at the wrong level, leading to a superficial (and potentially dangerous) analysis or an analysis that is bogged down in too much detail.
- Too much emphasis on historical records and failure data - see section 2.5.8.
- The analysis is performed by one person, not a group. Moubray asserts that one person alone cannot possess all the knowledge required to perform the analysis - refer to 2.5.1.
- Failure to include operators in the review. RCM is a holistic maintenance methodology and requires active engagement and enthusiasm from the equipment operators.

- Engaging the manufacturer to apply RCM independently is not considered effective, for reasons detailed in section 2.4.4. Engaging the manufacturer to participate in the RCM is positive.

- Engaging third parties to perform the RCM is not recommended because they may not have sufficient understanding of the operating context, contractual arrangements can disrupt the RCM process, and once the consultant leaves after finishing the project, there may be a lack of program ownership within the organisation.

- Over-emphasising the value of computers in the process. Much of the RCM process can be completed by a computer (Gabbar et al. 2003), but Moubray asserts that software cannot replace experienced tradesmen, operators and engineers.

## 2.6 Diesel Engine Condition Monitoring

### 2.6.1 Oil Sampling and Analysis

#### Spectrographic Analysis

Macian, Tormos, Olmeda & Montoro (2003) write that spectrography is the most widely used method of analysing oil contaminant particles. It is used to determine the elements and compounds that make up the contaminating particles, giving clues about which engine components may be deteriorating or what types of contaminants are entering the system. Thomas (2014) and Cummins Filtration (2014) support this, both providing a table of wear elements and the likely source.

The primary limitation of spectrography is that it only detects elements up to a certain size (Macian et al. 2003). Roylance (2005) supports this, indicating the maximum size is approximately 10 micrometres. Roylance (2005) advises that, for magnetic particles, this limitation is partly mitigated by using the Particle Quantifier (PQ) Index.

The PQ index measurement is an arbitrary index that does not convert to a unit of measurement. It is taken by subjecting an oil sample to a magnetic field. The magnetic field is disrupted proportionally to the amount of magnetic material in the sample. If the PQ index rises while the spectrography result stays constant, the test indicates that large wear particles are being generated. This result warrants further investigation, using analytical ferrography (Johnson 2011).

#### Fuel Injection System Monitoring

Macian, Payri, Tormos & Montoro (2006) present a technique for monitoring fuel injection systems using ferrography. A 100mL sample is taken, and magnets and a membrane separate the particles from the sample. The particles are analysed using optical and electron microscopy. Particles that can be detected include wear particles (sizes greater than 30 micrometres indicate a problem), dust and assembly debris. The test is focussed on detecting wear and incipient problems in high pressure and low pressure pumps.

#### Other oil analysis techniques

A wide variety of oil analysis techniques are available and are explained by Roylance (2005), Cummins Filtration (2014), Mollenhauer & Tschke (2010, pg. 369-370) and Thomas (2014). However, these pertain to the lubricating oil system, which has not been analysed; as such, they are considered out of the scope of this literature review.

### 2.6.2 Acoustic Emissions (AE) and Airborne Acoustics

Mba & Rao (2006, pg. 2-3, 7) write that analysis of the noise emitted from rotating machinery can provide cost-effective, reliable, sensitive diagnostic tools that are more sensitive than vibration analysis on machinery including pumps, gearboxes, bearings, engines and rotating equipment. AE analysis analyses component surface acoustics (discrete from vibration analysis), covering frequencies from 100kHz to 1MHz, while Airborne Acoustics monitors sound transmitted through the air to a microphone. Emissions are classified as continuous waveforms (e.g. turbulent fluid flow) or burst waveforms (e.g. meshing gears or rolling element bearing defects). Elamin, Fan, Gu & Ball (2009) advise that AE has a higher Signal to Noise Ratio (SNR) than vibration or pressure measurement. Kim, Tan & Yang (2012) agree, but they write that the SNR on combustion engines is lowered by severe noise generated by a variety of mechanical events. The primary drawback with both AE and airborne acoustics analysis is that the sensor must be placed close to the source, or the signal will be subject to attenuation and noise interference (Mba & Rao 2006, pg. 2-3) (Elamin et al. 2009).

The most popular applications of AE analysis on combustion engines are the non-intrusive detection of cylinder valve leakage, valve lash faults and defective diesel injectors, during operation (Salathiel, G 2014, pers. comm., 09 June)(Elamin et al. 2009)(Mba & Rao 2006). Elamin et al. (2009) presented a research paper detailing the successful analysis of valve clearances through surface AE on a 2.5 litre Ford four-stroke diesel engine. As the valve clearances were modified, the valve opening and closing timing changed and this was successfully detected and measured by the team. Lowe (2013) presented similar work with successful results. In a later paper, Elamin et al. (2010) successfully detected seeded injector faults in a four-stroke diesel engine. The faults included:

- Injector opening pressure 15 % low
- Injector opening pressure 20 % high
- No fuel supply to the injector

Lowe (2013, pg. 73-76, 142-143) supports the detection of injector faults using AE and was able to identify AE signatures for seeded faults including:

- Injectors delivering low fuel volumes (20% and 80% reductions were tested)
- No fuel supply to the injector
- Pintle type nozzles with incorrect pintle geometry and no pintle (indirect injection engines only)

Albarbar, Gu & Ball (2010, pg. 15) were able to decompose the engine emissions to measure piston slap, fuel injection, combustion and valve movements using airborne acoustics. The measurement and data processing calculations were claimed to yield promising results for detecting weak fuel injector springs under high load and low speed. Elamin et al. (2010) supports Albarbar et al. (2010) by noting that combustion, piston slap, fuel injection and valve impact are the most significant sources of AE in an engine.

Douglas, Steel & Reuben (2006) presented research on non-intrusive AE analysis of the tribological behaviour of the piston ring and liner interface. The force exerted on the piston sealing rings by the cylinder combustion gas pressure dominated the results, limiting the ability to detect the piston ring and liner interface signal.

### 2.6.3 Other Condition Monitoring Tools

#### Cylinder Pressure Measurement

Cylinder pressure measurement provides data on parameters such as:

- Peak firing pressure
- Compression pressure
- Mean effective pressure
- Maximum pressure rate rise
- Other thermodynamic properties for combustion diagnosis

(Lowe 2013, pg. 12-14)

Windrock, Inc. (2013) markets products that require cylinder pressure monitoring, indicating that the technique is well developed. However, Lowe (2013, pg. 12-14) writes that cylinder pressure measurement has been used to evaluate engine condition in a condition monitoring context, but is best suited to research, design and testing scenarios due to the intrusive nature of the method. Lowe (2013, pg. 12-14) acknowledges that piezo-electric sensors are being deployed in glow plugs, which may provide future potential for non-intrusive cylinder pressure measurement.

#### Crank Angle Measurement

Crank angle measurement measures the small variations in angular acceleration and speed, using pre-existing crank and cam sensors. The data obtained can be used to calculate cylinder pressures and engine torque. It has been used to detect under-fuelling, misfiring and external high pressure fuel leaks, but is only capable of detecting faults that are serious enough to affect the engine performance rather than detecting incipient problems that are precursors to poor engine performance (Lowe 2013, pg. 14-16).

#### Exhaust Gas Analysis

The temperature of exhaust gas can be analysed to monitor fuel to air ratios, fuel quality and cylinder power balance. Exhaust pressures can be analysed to provide detection of misfiring cylinders, incorrect fuel delivery and incorrect exhaust valve lash. The instrumentation is vulnerable to build-up of combustion by products, restricting the ability of the sensors to obtain data (Lowe 2013, pg. 16-17).

## 2.7 Life Data Analysis - The Weibull Distribution

#### Inception

The Weibull distribution function was first made widely known by Waloddi Weibull in his 1951 ASME Journal of Applied Mechanics paper ‘A statistical distribution function of wide applicability’. The Weibull distribution is now regarded as the best practice method for modelling equipment service life data (Weibull 1951) (Abernethy 2006, pg. 1.1).

#### Applications of Weibull analysis

The Weibull distribution can be used to model a wide variety of phenomena, but has found particular relevance in the field of reliability engineering. It is established as a robust, well known and versatile distribution used to model component life data (O’Connor & Kleyner 2011, pg. 78). The Weibull distribution can be applied to large failure datasets, but it can also be used with sample sizes as small as two or three failures; the Weibull distribution is the best choice for any dataset with less than 20 failures (Abernethy 2006, pg. 1.2-1.3,1.6).

A Weibull analysis can serve to:

- Benchmark equipment performance by comparing the characteristic life ($\eta$) against known standards or other operations.
- Identify the failure pattern according to the $\beta$ value(early life unreliability, random failure or a wear-out failure mode).
- Forecast failure counts (directly aiding maintenance planning and spare parts inventory analysis).
- Check and evaluate previously implemented failure countermeasures.
- Warranty and support cost predictions.
- Make recommendations to plant management for emergency failure management policy selection.

(Meridium 2012, pg. 2), (Abernethy 2006, pg. 1.2)

The limitations of a Weibull analysis that an analyst should be aware of are:

- Mixed or unknown failure modes can cause inaccurate results. Ideally, a Weibull analysis is performed on a single failure mode (Abernethy 2006, pg. 1.4).
- Small sample sizes reduce statistical relevance.
- Missing data points and incomplete datasets can compromise the results.

(Abernethy 2006, pg. 1.2)

### Two Parameter Weibull Cumulative Failure Distribution Function

$$F(t) = 1 - e^{-(\frac{t}{\eta})^{\beta}} \tag{2.1}$$

where:
$F(t)$ represents the cumulative failures,
$t$ is time,
$\beta$ is the 'shape' parameter,
$\eta$ is the 'scale' parameter, or 'characteristic life'. It represents the time at which 63.2% of the population will have failed.
(O'Connor & Kleyner 2011, pg. 78)

**Weibull Probability Plot**

The Weibull probability plot uses modified axes. The Y-axis is a double natural logarithm reciprical and the X-axis is a natural logarithm. When failure data that can be modelled by the Weibull distribution is plotted on this chart, it will form a straight line, of the form $Y = mX + C$.

$$ln(ln(\frac{1}{1 - F(t)})) = \beta(ln(t)) - \beta(ln(\eta)) \tag{2.2}$$

Where:
$ln(ln(\frac{1}{1-F(t)})) = Y$
$\beta = m$
$(ln(t)) = X$
$\beta(ln(\eta)) = C$

(O'Connor & Kleyner 2011, pg. 78)

**Data ranking and treatment of 'censored' data**

O'Connor & Kleyner (2011, pg. 75-76) discuss the ranking of data and provide an example of 5 specimens that fail at a service life of 100, 200, 300, 400 and 500 hours respectively. In a rudimentary analysis, an analyst would infer that 20% of the population will fail by 100 hours and 100% of the population fails by 500 hours. However, given that each failure represents a point on a probability distribution, the percentage must be adjusted. For a distribution such as the Weibull distribution that does not usually match the normal distribution, the median rank may be used. For the sake of an example, the algebraic approximation of the median rank is:

$$r_j = \frac{j - 0.3}{N + 0.4} \tag{2.3}$$

Where:
$r_j$ is the median rank
$j$ is the failure number, listed from smallest to largest by service life

$N$ is the sample size

Data sets will often include data points that survived a service life and were then removed from service, with no failure occurring. This data is counted as 'censored', and mathematically affects the ranking of the failures in the dataset. This is achieved by modifying the order number of each failure:

$$i_{t_i} = i_{t_{i-1}} + N_{t_i} \tag{2.4}$$

Where:
$i_{t_i}$ is the mean order number of the i$th$ failure, similar to $j$ in equation 2.3
$i_{t_{i-1}}$ is the mean order number of the preceding failure
$N_{t_i}$ is defined by:

$$N_{t_i} = \frac{(n+1) - i_{t_{i-1}}}{1 + (n - n_{i_{censored+failed}})} \tag{2.5}$$

Where:
$n$ is the total sample size
$n_{i_{censored+failed}}$ is the number of items that have failed or were removed from service prior to failure up until the i$th$ data point.

**Data required for Weibull analysis**

To perform a Weibull analysis, the following data is required:

- Asset identification (particularly relevant for fleets of equipment)
- Installation date
- Failure date
- Failure mode
- Downtime (optional, used to improve accuracy of service life)

If the equipment is not repaired or replaced to a new standard after failure (i.e. it is 'as good as old'), the following information is also required:

- Number of components in a system or asset. For example, there may be 12 pumps in a pump-set.
- At each event, the data must specify whether or not the system or asset was returned to 'as good as old' or 'as good as new' condition.
- The number of components that failed at each failure event.

(Meridium 2012, pg. 3-4)

### Interpreting Weibull results

The values of $\eta$ and $\beta$ provide the basis for interpreting the Weibull results. In general, $\eta$ indicates whether the equipment life is relatively short or long, while the $\beta$ value indicates the failure pattern of the equipment. For example:

$\beta < 1$, the equipment will fail more often early in life and the reliability will increase with time. Generally, no time-based maintenance will improve the reliability.
$\beta \approx 1$, the equipment will fail randomly. Time-based maintenance will neither improve nor reduce the equipment reliability.
$\beta > 1$, the equipment will 'wear out' and scheduled maintenance should be undertaken when the risk of failure becomes too great.
(Abernethy 2006, pg. 1.4)

A good Weibull probability plot will place all failures on a single linear line. 'Doglegs' or 'corners' in the data can indicate mixed failure modes, while curves can indicate a dataset that does not fit the Weibull distribution (Abernethy 2006, pg. 1.8).

The Weibull results must be checked for Goodness Of Fit (GOF), to ensure that the results are valid. The Rio Tinto Reliability Solution (RTRS) has the capability to use the least squares linear regression method (greater than 0.9 is considered a good fit) or the Kolmogorov-Smirnov method, which yields a 'p-value'. If the 'p-value' is greater than one minus the required confidence level, the results are considered accurate enough to make a prediction (Meridium 2012, pg. 3).

## 2.8 Selected Engine Component Failure Mode Research

### 2.8.1 High Pressure Diesel Pumps

#### Pump Function

The primary function of the pump is to provide high pressure fuel to the injector. Energy is supplied via a rotating camshaft and fuel delivery is controlled by the Engine Control Unit via a solenoid (GE Transportation 2012*a*, sec. 7 pg. 3).

#### Pump Cavitation damage

Cavitation occurs when vapour bubbles are formed in a liquid below its vapour pressure and the liquid is then subjected to a large, rapid rise in pressure. The bubbles collapse with an explosive force, damaging and deforming the component surface (Asi 2006). Due to the high pressures and pressure differentials in diesel injection systems, cavitation is common and is accelerated when water is present (Greuter & Zima 2012, pg. 394).

Greuter & Zima (2012, pg. 394) advise that high pressure diesel pumps are susceptible to cavitation, providing the example of a pump plunger suffering cavitation damage. The areas most susceptible to cavitation are the plunger and the pump housing, adjacent to the spill port.

#### Water Ingress

Water ingress will enable corrosion to take place and reduce the lubrication capacity of the diesel, severely accelerating wear (Greuter & Zima 2012, pg. 395).

#### Dirt Ingress

Dirt ingress or fuel contaminants (including water) will degrade the lubricating properties of the fuel and lead to seizure (Greuter & Zima 2012, pg. 395).

**Wear**

Wear is inevitable during service and if allowed to progress will decrease pump efficiency and capability to deliver the appropriate amount of fuel (Greuter & Zima 2012, pg. 398) (Macian et al. 2006).

### 2.8.2 High Pressure Diesel Injectors

**Injector Functions**

The functions of the diesel injector are to:

- Inject fuel precisely without leakage
- Atomise the fuel
- Direct the spray evenly throughout the cylinder without wetting the cylinder walls and piston

(Dempsey 2008, 78)

**Injector Cavitation damage**

Asi (2006) examines a cracked injector and determines that the cause of failure is cavitation, leading to fatigue cracking. Greuter & Zima (2012, pg. 394) support this, stating that cavitation can lead to wear, cracks and fatigue fractures.

**Breakaway of the atomiser body (Uncapping)**

Bejger (2011) presents a case study on injectors that have ‘uncapped’. Once uncapped, the atomiser body is then a loose object in the cylinder that causes significant secondary engine damage. One set of injectors failed due to a combination of poor quality fuel and wear (unfortunately, no further detail is provided) while a second set failed due to poor manufacture quality.

Greuter & Zima (2012, pg. 398) specifically discuss wear on the injector pin, which allows the needle to lift further. This increases the energy stored in the injector spring, which magnifies the impact of the needle reseating on the valve, leading to uncapping.

#### Seizure

Injector seizure affects the needle, making it seize in the injector body and fail to return to the valve seat, allowing low pressure diesel to enter the cylinder. Low pressure fuel will be ejected as a stream rather than in an atomised spray and may leak droplets onto the piston.

Injector seizure may be caused by dirt particles and fuel with inappropriate lubrication properties (Von Wielligh, Burger & Wilcocks 2003).

#### Leaking

If fuel droplets are leaked directly onto the piston and burn, the droplets will overheat and melt the piston, causing engine failure. Leakage can be caused by a seized or worn injector (Von Wielligh et al. 2003).

#### Poor spray pattern

Dempsey (2008, 79-80) states that a poor spray pattern can be caused by:

- Low injection pressure
- Injector seizure
- Broken injector spring
- Dirt or foreign material on the valve seat or injection port
- Injection port damage or abnormal wear
- Carbon build-up
- Uneven seat contact

Von Wielligh et al. (2003) provides a case study on engine failure due to poor spray pattern, describing cases showing that if fuel flows onto the cylinder walls, it will wash away lubricating oil and lead to piston scuffing or seizure.

**Spring failure**

Greuter & Zima (2012, pg. 396) advises that spring failure is generally caused by fatigue cracking at the flat-ground ends of the springs or material weaknesses (inclusions or surface finish defects).

### 2.8.3 Cylinder Liners

The cylinder liner is a heavy walled tube that performs the following functions:

- Provides the combustion chamber and sealing surfaces for the piston.
- Guides the piston.
- Retains oil within the surface honing for lubrication.
- Transfers heat to the coolant.

Cylinder liners are subjected to mechanical, thermal, chemical and tribological loads (Greuter & Zima 2012, pg. 291).

**Tribological failure modes**

Wear is an inevitable result of engine operation. Greuter & Zima (2012, pg. 299-305) identify the following modes as prominent in cylinder liner failure and broader engine failures:

- At top dead centre (TDC) the lubricating oil film between the piston rings and cylinder liner breaks down due to contact with extremely hot, pressurised combustion gases. Sulfurous combustion by-products resulting from poor quality fuel and excessive gas pressures can aggravate the problem (Greuter & Zima 2012, pg. 300). Dempsey (2008, pg. 207-208) agrees, noting that the wear is caused by localised oil starvation and combustion related acids.

- Abrasive wear can be driven by poor quality fuel introducing wear particles, but may also result from the carbon particles that are a by-product of the combustion process itself. Abrasive wear 'polishes' the bore and removes the bore hone marks. Bore polishing leads to poor cylinder sealing, increased oil consumption and piston seizure due to oil starvation.

- Adhesive wear is caused by the fusion of two asperities on sliding surfaces; one of the asperities is subsequently torn away from the cylinder liner (or piston sealing ring) (Askeland & Phulé 2006, pg. 832-833). Shuster, Mahler & Crysler (1999) support this; evidence of the early stages of adhesive wear was found in an engine during metallurgical analysis of a heavy duty diesel engine after testing.

**Liner Pitting - Cavitation Corrosion**

Mechanical movement and vibration of the cylinder liner induced by piston loading can cause cavitation in wet cylinder liners. Greuter & Zima (2012, pg. 305-307) note that if there is enough oxygen in the coolant, the process can be accelerated and termed cavitation corrosion.

Hercamp (1993, pg. 114-121) provides a detailed treatment of cavitation corrosion of cylinder liners. A number of causes and contributing factors are identified in terms of engine design for reducing vibration, but in the maintenance sphere of control, coolant concentration and composition are important for preventing cavitation. Hercamp (1993, pg. 114-121) provides further detail but this is considered out of the scope of this literature review, as the cooling system has not been analysed.

**Cracks and Fractures**

Greuter & Zima (2012, pg. 307-308) advise that cylinder liner cracking often occurs around the top flange mounting in the jacket and is caused by incorrect head gasket, component dimensions or installation. Poor coolant concentration or composition can contribute to crack growth by introducing corrosive attack.

### 2.8.4 Cylinder Head and Cylinder Jacket

The cylinder head forms the upper boundary of the combustion chamber and has the following features and functions:

- Facilitates the flow of coolant and lubricating oil.
- Houses the intake and exhaust valves and valve seats and associated components (springs, guides, etc.).
- Houses the fuel injector.
- Facilitates the flow of fresh air and combustion gases (courtesy of the valve train).
- Stiffens the engine structure. Dempsey (2008, pg. 139) promotes the cylinder head as the head gasket backing plate; it is stated that the stiffness of the cylinder head is the most important design feature.

(Greuter & Zima 2012, pg. 309) (GE Transportation 2012*a*, sec. 10 pg. 3)

Large, heavy duty engine cylinder heads are made of iron (Dempsey 2008, pg. 139). Greuter & Zima (2012, pg. 310) specify nodular or lamellar grey cast iron or cast steel for certain applications. Valve seats and guides are often replaceable inserts.

**Cylinder head gasket failure**

Greuter & Zima (2012, pg. 317-318) identify that cylinder head gasket leaks can be caused by:

- Poor assembly quality - if particles are trapped between the block, gasket and head, the seal quality will be compromised.
- Engine overheating, causing physical degradation of the gasket material.
- Incorrect engine head stud torque or torqing procedure (Dempsey 2008, pg. 174-175).
- Lack of maintenance of head gaskets that require re-torqing.

The effects of cylinder head leaks include exhaust gases leaking into the cooling system and coolant leaks into the cylinder, leading to hydraulic lock in the worst case (Greuter & Zima 2012, pg. 318).

**Cylinder head distortion**

The cylinder head can become distorted due to overheating. Single-cylinder iron/steel heads are less prone to cylinder head distortion than multiple cylinder aluminium heads. Aluminium introduces different thermal expansion rates, and multiple cylinder heads form a bigger component over which distortion can occur. Distortion can cause head gasket leaks (Dempsey 2008, pg. 139, 164) (Greuter & Zima 2012, pg. 316).

**Erosion and Corrosion**

Erosion can occur in cylinder head coolant passages if the coolant contains fine particles of an abrasive nature (Greuter & Zima 2012, pg. 315). Dempsey (2008, pg. 159) notes that joins and interfaces (ports) should be thoroughly checked for erosion. Hercamp (1993, pg. 114-121) discusses the importance of correct coolant concentration and composition to prevent corrosion from enhancing cavitation or corrosion, as erosion-corrosion acts much faster than either mechanism individually (Kosel 1992, pg. 199-213).

**Cylinder head cracking**

Cylinder head cracks are caused by thermal and mechanical stresses. Thin webs that bridge between exhaust valves or between intake valves are prone to cracking caused by low-cycle thermal fatigue, due to engine load changes and starting. The cracking is assisted by the high cycle mechanical loading (Greuter & Zima 2012, pg. 313-314).

A causal factor of thermal overloading is scale deposits in the cooling system, further stressing the requirement for coolant with proper concentration and composition. These deposits thermally insulate the area covered by the deposit, which causes overheating to occur in small areas (Greuter & Zima 2012, pg. 313-314).

Dempsey (2008, pg. 161-163) discusses the severity of cracks; any cracks that extend between engine systems (such as cooling, lubrication, intake and exhaust or combustion) render the component unserviceable, but cracks protruding a short distance in other areas may not affect the service life of the component.

Manufacturing defects, including shrinkage voids and inclusions, can cause cracking (Greuter & Zima 2012, pg. 314).

### 2.8.5 Valve Train

The function of the valve train is to allow the intake of fresh air, seal the combustion chamber and allow the exhaustion of combustion gases. The valve train is comprised of the following major components:

- Valves, valve guides and valve seats to provide the sealing surface.
- Valve springs to hold the valve against the valve seat and away from the piston.
- Pushrods, cam followers and the rocker assembly to extract energy from the rotating camshaft and depress the valve.

(Dempsey 2008, pg. 144-145) (Greuter & Zima 2012, pg. 318)

Valves and valve seats are subject to mechanical forces (opening and closing forces and combustion pressure), cyclic thermal loads (intake valves reach 600 degrees Celsius and exhaust valves can reach 1000 degrees Celsius during the combustion and exhaust phase, and cool during intake and compression), tribological loads and hot chemical corrosion (Greuter & Zima 2012, pg. 328-329). Exhaust valve seats experience harsher service conditions due to higher thermal variation and corrosive by-products contained in exhaust gases (Greuter & Zima 2012, pg. 330-331).

Valve springs are compressed and released at a high cycle rate, subjecting the component to cyclic torsional loading. Valves must possess high resistance to fatigue cracking by having a very good surface finish and being constructed from appropriate, homogeneous materials (Greuter & Zima 2012, pg. 322-323).

The pushrods, cam followers and rocker assembly are subject to mechanical loads. Pushrods are subject to compression loads as high as 40,000 Newtons. Cam followers are subjected to the same loading but as Hertzian stresses (Greuter & Zima 2012) and a boundary lubrication interface with the camshaft (Priest & Taylor 2000).

**Burnt valve disc**

Burnt valves occur when the valve is heated to the material melting point and the material is removed by gas flow (Greuter & Zima 2012, pg. 333). This failure mode can cause the removal of a large amount of material from the valve, eliminating the ability to form a seal.

Dempsey (2008, pg. 167) writes that burnt valve discs can occur as a result of:

- Abnormal temperatures in the combustion chamber. Greuter & Zima (2012, pg. 332) advises this can be due to improper fuel injection.
- A cooling system fault.
- As a result of insufficient valve lash. The valve seat provides cooling for the valve disc, so insufficient valve lash holds the disc off the valve seat, removing the cooling capacity of the seat and leading directly to burnt valves.

(Greuter & Zima 2012, pg. 332-333) adds further failure modes:

- Faulty valve rotation can allow the valve to overheat in a localised area.
  - Valve rotator faults can occur due to valve stem misalignment, which raises the friction resistance in the rotator, or due to contamination (Greuter & Zima 2012, pg. 342).
- Deposits on the valve seat can inhibit cooling of the valve disc.
- If the valve does not seal properly against the seat, blow-by and overheating can occur.

### Valve fatigue fracture

Valve fatigue fracture is most often caused by cyclical shock loading or bending (Dempsey 2008, pg. 167). Some of the common causal factors include:

- Vibration in the valve train (Greuter & Zima 2012, pg. 333-334).
- Weak springs, allowing:
  - Valve float - the valve is not held tight against the cam roller and 'floats', causing impact upon reseating.
  - Valve bounce - upon reseating, the valve bounces on the valve seat (Dempsey 2008, pg. 167) (Greuter & Zima 2012, pg. 334).
- Excessive valve lash causes the valves to lift and reseat while the cam lobe is on the flanks, causing impact (Dempsey 2008, pg. 167). The valve should reseat on the cam lobe ramps, which are designed to decelerate the valve and lessen the reseating force (Greuter & Zima 2012, pg. 343).

### Valve wear

Valve seats can wear prematurely due to incorrect valve clearance settings, high velocity abrasive particles in the gas flow, and overheated exhaust gases (Greuter & Zima 2012, pg. 312,342). Exhaust valves are protected somewhat by the layer of hard-facing and a build-up of non-metallic particles; however, heavy build-up combined with valve rotators can cause scoring (Greuter & Zima 2012, pg. 335).

### Valve seizure

The following causal factors for valve seizure are identified:

- Dempsey (2008, pg. 167) and Greuter & Zima (2012, pg. 315) agree that carbon and gum build-up can cause the valve stem to stick and seize.
  - Greuter & Zima (2012, pg. 335) advise that over-extended oil drain intervals and incorrect oil can contribute to carbon build-up.

- Fuel burning characteristics at low temperature can cause gum to build-up. Low temperature can be caused by long periods at idle or excessively low operating temperatures (Dempsey 2008, pg. 167).
- Ethylene glycol presence in the lubricating oil can contribute to a gum build-up (Dempsey 2008, pg. 167).
- Lubricant starvation (Greuter & Zima 2012, pg. 335).
- Misalignment (Greuter & Zima 2012, pg. 335).
- Insufficient clearance between the stem and guide (Greuter & Zima 2012, pg. 335).

Valve seizure can result in a piston strike and severe secondary damage to the engine.

#### Valve stem and guide wear

Dempsey (2008, pg. 165) discusses the side-loading of valves from the rocker assembly, causing the valve guide to wear an eccentric shape at the top and bottom of the valve guide. The wear at the top encourages oil to leak down into the exhaust port, while the wear at the bottom invites carbon build-up, which causes premature valve stem wear and scoring.

Fretting corrosion may occur at the valve stem keepers and initiate fatigue cracking, causing a valve to drop into the combustion chamber (Greuter & Zima 2012, pg. 337).

Sulfurous by-products from combustion contribute to valve wear (Greuter & Zima 2012, pg. 339).

#### Valve spring failure modes

Valve springs fail due to fatigue cracking that may be initiated by very minor surface flaws or material inclusions. Additionally, failure may occur at the interface between the spring end and the cylinder head due to fretting corrosion initiating fatigue cracking (Greuter & Zima 2012, pg. 325).

Dempsey (2008, pg. 170-171) advises that due to the minor nature of defects required to produce the severe consequences of the engine 'swallowing a valve' (the valve dropping into the combustion chamber), valve springs should be replaced at each overhaul no matter what assessment the technician has made of their condition.

### Corrosion and hot corrosion

General corrosion is primarily driven by sulfurous combustion by-products dropping below their dew point and forming acids. The following conditions contribute to general corrosion:

- Low quality, high sulfur fuel
- Low acid neutralisation capacity in the lubricating oil
- Continuous low running temperatures, allowing condensation of sulfurous by-products
- Excessive blow-by

(Greuter & Zima 2012, pg. 339)

More specifically, Greuter & Zima (2012, pg. 316-317) advise that valve guides are prone to corrosive attack. If sulfurous by-products and any moisture in the exhaust gases are deposited in the valve guide, premature material removal will occur. Factors contributing to this are low quality, high sulfur fuel, and incorrect dimensions or clearance at the valve stem and valve guide interface.

Hot corrosion involves heavy metal-oxide by-products (Sulfur, Vanadium and Sodium) that react to form low melting point salts. The salts deposit on the high temperature exhaust valves, producing the following effects:

- The protective passivating metal oxide layers on the valve are dissolved by the salts.
- Alloying elements are drawn out of the valve material.

- Oxygen is harboured by the salts in contact with the valve, increasing the corrosion rate.
- The salts deposit unevenly on the valve sealing surface allowing leakage. This leakage develops localised heating and eventually burnt valves.

To counteract the problem, leaner fuel mixes can be used, or design changes to the valve and valve cooling can be made (Greuter & Zima 2012, pg. 340-341).

### 2.8.6 Pistons

The primary functions of the engine piston are to provide the bottom surface of the combustion chamber, and to transmit power to and from the combustion gasses (Greuter & Zima 2012, pg. 99-100).

**Piston seizure**

Piston seizure can be caused by the following conditions:

- Uneven head torque warping the cylinder, which leads to piston contact (Greuter & Zima 2012, pg. 115).
- Overheating due to cooling defects or combustion chamber abnormalities causes expansion of the piston, eliminating the lubrication clearance.
- Excessively smooth cylinder bore that does not have appropriate hone marks.
- Broken piston rings.
- Lubrication system failure.
- Oil dilution by fuel causing oil starvation.
- Fuel flooding, washing the lubricant from the cylinder bore.

(Greuter & Zima 2012, pg. 115-135)

Dempsey (2008, pg. 219-221) writes that seizure is caused by lubricant starvation, contamination, overheating, harsh combustion and poor assembly quality.

**Wear**

Piston wear is predominantly caused by:

- Dirt ingress, through the lubricating system, fuel system or combustion air system.
- Poor manufacturing techniques.

(Greuter & Zima 2012, pg. 125-126) (Dempsey 2008, pg. 219)

**Piston burn-through and melting**

Piston burn-through, or holing, can occur due to poor fuel injection and overheating (Greuter & Zima 2012, pg. 144-150). Dempsey (2008, 219) supports this, advising that rough combustion (referred to as detonation damage) erodes the piston leading to holing.

**Piston head deformation**

Deformation can be caused by contact with the cylinder valves, due to incorrect timing, incorrect clearance, broken valve springs, or valve seizure (Greuter & Zima 2012, pg. 151-154).

**Piston cracking**

Cracking of the piston, ring land, wrist pin and the associated wrist pin bore, retainer and boss can be caused by:

- Fatigue cracking.
- Harsh combustion and overloading caused by:
  - Poor fuel injection

  - Incorrect fuel to air ratios, which can be caused by clogged air filters or leaks.
  - Engine cooling problems
  - Excessive use of starting aids

- Overheating.
- Poor quality assembly or casting defects.
- Excessive piston-cylinder wall clearance. This causes the piston rings to sit out further, increasing the stress on the ring groove. Additionally, it emphasises the contact between the cylinder wall and the piston skirt.
- Water accumulation while the engine is shut down, causing hydraulic lock.
- Piston head and wrist pin bore, caused by high-temperature mechanical fatigue.
- Sealing ring grooves, caused by high clearance between the clyinder wall and piston (supporting Greuter & Zima (2012, pg. 137-142) Dempsey (2008, pg. 221)).
- Piston skirt, also caused by high clearance, which emphasises contact between the cylinder and bottom of the skirt.

(Greuter & Zima 2012, pg. 137-142, 164-176) (Dempsey 2008, pg. 221) (Silva 2006) Unterweiser, F.R., Hutchings, P.M. (1981) Martin (2004)

Unterweiser, F.R., Hutchings, P.M. (1981) presents the case of a wrist pin failure due to fatigue cracking, which initiated in a non-metallic inclusion.

#### Piston ring failure

Piston rings can experience the following failure modes:

- Fracture due to:
  - Harsh combustion.
  - Insufficient clearance once fitted to the piston/cylinder.

  - While fitting the rings to the piston, they must be opened up. If this is done incorrectly, it can directly lead to fracture.

- Preload loss, reducing the sealing effectiveness.
- Wear, for the same reasons that cylinder liners and pistons suffer wear.
- Burned rings, due to piston overheating, which compromises lubrication.
- Stuck rings, due to piston overheating that has burnt the lubricating oil. The residue causes the rings to become stuck and they can no longer perform their sealing function.

**Wrist pin liberation**

If the retaining ring is damaged, the wrist pin may be able to float free and contact the cylinder wall, leading to catastrophic damage. This can occur due to poor fitment, bent connecting rod or crankshaft and excessive crankshaft end float (Dempsey 2008, pg. 221).

### 2.8.7 Connecting Rods

Diesel engine connecting rods transfer the linear power developed in the combustion chamber to the rotating crankshaft; their reliability is of critical importance to engine safety and failures are often catastrophic. Thus, they are conservatively designed and are constructed from a forged medium alloy steel (GE Transportation 2012*a*, sec. 10, pg. 5)(Dempsey 2008, pg. 226).

**Fatigue cracking**

Connecting rods are susceptible to fatigue cracking in the bearing housings and body (Dempsey 2008, pg. 231-233). This is supported by Rabb (1996) in an analysis of a failed connecting rod.

Greuter & Zima (2012, pg. 197-202) provide examples of fatigue cracking initiating from:

- Manufacturing and maintenance damage, including small nicks, grind marks and other slight damage.
- Fretting corrosion between the bearing and bearing housing, due to low bolt pretension or incorrect dimensions.
- Opening of the bearing mating faces and subsequent bolt failure due to low pretension.

**Bent connecting rod**

Dempsey (2008, pg. 229-230) advises that a bent connecting rod will cause overloading in the connecting rod bearings and abnormal wear patterns on the piston skirt. Greuter & Zima (2012, pg. 202-203) advises that bent connecting rods are primarily due to secondary damage, resulting from piston seizure or hydraulic lock that is caused by coolant, oil or fuel leaking into the cylinder.

### 2.8.8 Bearings

The function of the wrist pin and crankshaft journal bearing set is to:

- Transfer heat.
- Wash away wear particles.
- Reduce friction.
- Separate metal surfaces.
- Transfer force.

(Greuter & Zima 2012, pg. 215, 221-222)

Crankshaft journal and wrist pin bearings are of the plain bearing type, because they are able to be heavily loaded, operate at high speeds, have a long service life, are suitable to be manufactured in two halves (for efficient assembly) and are relatively simple to manufacture (Mollenhauer & Tschke 2010, pg. 259).

**Contamination, Wear and Erosion**

Mollenhauer & Tschke (2010, pg. 269) advises that low rates of wear are normal and do not cause harm. However, if the lubricating barrier is compromised, abrasive wear can occur. Small particles can cause accelerated laminar wear and large particles can cause more serious scoring. If the wear rate increases and the operating temperature rises, adhesive wear becomes a risk, leading to total bearing failure.

Sources of wear particles can include:

- Particles liberated by cavitation
- Dirt and other foreign material
- Manufacture by-products, including sand, weld splatter and machining chips
- Engine operation by-products that have entered the lubricating oil

(Greuter & Zima 2012, pg. 233-240,249)

**Cavitation**

The cavitation mechanism is described in section 2.8.1. Bearing cavitation is caused by oil flow characteristics that cause the lubricant pressure to drop below the vapour pressure. Material liberated by cavitation causes wear and scoring to occur downstream of the cavitation area. Bearing cavitation can be aided by oil dilution and high bearing temperatures (Greuter & Zima 2012, pg. 243-249).

**Fatigue**

Fatigue damage occurs due to the cyclical loading inherent in the engine process; Mollenhauer & Tschke (2010, pg. 270) and Greuter & Zima (2012, pg. 240) agree that the loading pressure gradient has a greater affect than the load pressure magnitude. Greuter & Zima (2012, 241-242) advise that cracking will propagate in an axial direction until it reaches the steel backing and then will propagate along the circumference until a chunk of bearing liner material falls out. At each stage in the crack propagation, the lubricating function is reduced, leading to bearing failure.

#### Corrosion

Mollenhauer & Tschke (2010, pg. 269) write that corrosion generally occurs due to a lubricating oil system fault; this will not be explored any further, as the project has not covered the lubricating oil system.

#### Electrical Discharge

Greuter & Zima (2012, pg. 251-253) write that electrical discharge can be caused by welding and external voltage sources or inductive current from a generator. The arcing causes small areas to melt, which are subsequently washed out, leaving craters in the bearing material and reducing the lubricating function.

#### Assembly Defects

Assembly defects can include:

- Incorrect connecting rod bolt torque can cause bearing ovality in the vertical direction due to insufficient torque or ovality in the horizontal direction due to excessive torque, reducing the bearing's ability to develop a full oil film.
- Installation errors, including covered oil passages, locating lug and pin seating errors.
- Foreign material inclusions between the bearing and connecting rod bore, leading to fretting corrosion and fatigue cracking.

(Greuter & Zima 2012, pg. 258, 269-274)

### 2.8.9 Turbocharger

The turbocharger uses waste energy from the exhaust gasses to compress the charge air, increasing the engine capacity and efficiency (GE Transportation 2012*a*, section 16, pg. 4) (Greuter & Zima 2012, pg. 477). Greuter & Zima (2012, pg. 484-496) identify the following turbocharger failure modes:

**Manufacture defects** Manufacture defects include material inclusions leading to fatigue fracture.

**Impact damage** Items that are either left in the ducting or come loose following maintenance cause damage to the turbine and compressor.

**Imbalance** Due to the high rotational speeds, relatively small imbalances caused by uneven rotor deposits, uneven wear and faulty bearings can cause failure.

**Erosion** Erosion occurs if the exhaust gasses contain particles.

**Fatigue cracking** Fatigue cracking can be initiated by corrosion, foreign object impact, imbalance and high cycle fatigue (HCF) caused by self-induced vibration.

**Lubrication failure** Lubrication failure can be caused by lubricant contamination, oil starvation or over-aged oil.

**Oil leakage** Oil leakage can occur due to worn seals, excessive oil level or obstructed oil drain lines.

### 2.8.10 Intercooler

The intercooler function is to increase air density by cooling the hot, pressurised air discharged by the turbocharger (GE Transportation 2012*a*, section 8, pg. 17).

Greuter & Zima (2012, pg. 463-477) identify the following failure modes that can affect heat exchangers:

**Corrosion** Corrosion can be caused by poor coolant quality or contaminant ingress.

**Fouling** Fouling is the deposition of a layer of low thermally conductive material, originating in the coolant or due to a chemical reaction or biological growth.

**Fatigue and fretting corrosion** Vibration, thermal expansion and contraction and pressure shocks can cause fretting corrosion and fatigue in the heat exchanger.

**Blockages** Contaminants can reduce heat exchanger efficiency by clogging flow paths.

**Cavitation** Localised low pressure areas as a result of undesirable flow paths can result in cavitation.

## 2.9 Applicable Australian Standards and Regulations

- AS IEC 60300.3.11-2011 is the adopted Australian Standard for Reliability Centered Maintenance. It has been referenced heavily in this literature review.
- AS 4292.3-2006, the Australian Standard for Railway Safety Management of Rolling Stock, the Rail Safety Act 2010 and the Rail Safety Regulations 2011 do not detail specific requirements for locomotive maintenance or diesel engine maintenance. They generally address the need for adequate maintenance, the ability to keep maintenance records, and a requirement that the Rail Safety Regulator must be notified 28 days prior to implementing a change to the maintenance of rolling stock (Standards Australia 2006, pg. 15-16) (*Rail Safety Act* 2010, pg. i-xi, 27) (*Rail Safety Regulations* 2011, pg. 198, 228, 233).

## 2.10 Chapter Summary

In section 2.2, the literature reviewed has shown a distinct absence of academic literature detailing the formulation of maintenance tactics for locomotive engines working in the heavy-haul mining industry, in a hot semi-arid climate. The asset operational context is unique (refer to section 1.3), and the operating context has a significant impact on the maintenance tactics that are applied (section 2.2 and 2.4.4). As a result, the efficiency of RTIO's current maintenance tactics (adopted directly from the OEM standard recommendations, section 1.3) is not understood.

In section 2.3, the literature review has established that RCM is an effective methodology to evaluate and determine the appropriate maintenance tactics. Section 2.4.3 establishes that following the RCM process will develop a knowledge database of failure modes, effects and the risk that is mitigated by each maintenance task, fulfilling the research aims and objectives identified in the project specification (appendix A) and section 1.2). The project will pursue the application of the RCM methodology to the RTIO locomotive engine in order to develop an understanding of the efficiency of RTIO's maintenance tactics, failure modes and the risk mitigated by each maintenance task, contributing to the body of academic literature and knowledge in this area.

Seminal RCM publications, standards and academic research literature are reviewed in section 2.5, informing the project of the best practice RCM methodology to be applied to the project work. Most of these sources are clustered around the year 2000; the author did not find any significant recent publications, indicating that the methodology is mature and stable.

Section 2.5.1 identifies the knowledge required to perform an RCM analysis that did not exist at the commencement of the project, requiring development in the early stages of the project work. Each item is documented in chapter 3, but the key items of knowledge that required development include:

- Evaluation and prioritisation of the engine subsystems according to HSE risk, maintenance costs, corrective maintenance and production delays.
- Definition of the operational context.
- Reliability modelling and analysis of equipment failure modes.

  - In order to inform the project on best practice reliability modelling, literature on the topic of the Weibull distribution has been reviewed in section 2.7.

The literature reviewed found in section 2.5.1 that the RCM analysis participants must be informed by a knowledge and understanding of:

- Equipment condition, failure modes and failure modes being prevented by the current maintenance regime.
  - To address this requirement, a literature review of common diesel engine failure modes has been conducted by the author and included in section 2.8.
- Maintenance processes and novel maintenance techniques.
  - The literature review of condition monitoring technologies for diesel engines is included in section 2.6 to develop and demonstrate a sufficient knowledge in this area.
- Access to, and understanding of, relevant legislation and regulations.
  - A review of the relevant legislative and regulatory documents has been included in section 2.9.

The literature review has gathered the foundational information to inform and support the focus of the research, formulate the research methodology and develop the prerequisite knowledge to conduct the analysis.

# Chapter 3

# Reliability-Centered Maintenance Analysis Planning and Preparation

## 3.1 Chapter Overview

Chapter 3 provides a discussion on the planning phase of the RCM project. The planning phase was carried out according to the guidelines established in chapter 2, section 2.5.1 and includes the following tasks:

- Establish participant prior experience and knowledge (and develop or teach where necessary).
- Establish the objectives of the RCM.
- Determine the analysis level and subsystems.
- Define the asset and system boundaries.
- Prioritise the subsystems.
- Define the operating context.
- Gather relevant legislation and regulations.
- Gather relevant operating procedures.

## 3.2 Establish participant prior experience and knowledge

Due to resource constraints, the author was not able to assemble an RCM working group, although this is recommended by the literature (Standards Australia 2011, pg. 17) (Moubray 2001, pg. 267). As a result, the author took the approach to develop the framework of the analysis based on a literature review of failure modes, the author's own knowledge, ad-hoc consultation with senior tradesmen and a review of maintenance work orders. Following this process, a formal Failure Modes and Effects Analysis (FMEA) session was held with senior tradesmen to validate the analysis, cover any undocumented failure modes, and expand in detail on the failure effects.

The author developed a short presentation providing an overview of RCM and an FMEA worksheet (see appendix H) for the senior tradesmen who were involved in the FMEA analysis. The author believes this provided the relevant context to ensure the tradesmen were able to participate effectively.

The author developed the relevant RCM facilitator knowledge to carry out the RCM by conducting the project literature review. To gain access to the appropriate experience, the author consulted RCM experts within Rio Tinto.

In conclusion, the author believes that the approach was effective in this instance, and every effort to consult the equipment maintainers was made, although conditions were not ideal.

## 3.3 Establish Reliability-Centered Maintenance Analysis Objectives

The research project aims and objectives are distinct from the business or industry objectives; both facets of the project are detailed in this section in order to explicitly identify the difference between research aims and industry outcomes. The primary research aim is to determine whether RTIOs current maintenance regime is optimised and identify the failure modes and the risk mitigated by each maintenance task (further detail is provided in section 1.2). The primary business objectives and focus of this RCM analysis is to:

1. Reduce maintenance cost
2. Improve HSE performance and reduce risk
3. Improve equipment reliability

This will be achieved by:

- Eliminating unnecessary scheduled maintenance tasks.
- Refining the maintenance tasks that are undertaken.
- Recommending maintenance tasks that prevent failures and reduce corrective maintenance cost.
- Reducing maintenance intervention; this reduces potential HSE incidents, as maintenance tasks have the potential to contribute to a HSE incident.
- Identification of proactive maintenance tasks that will reduce HSE risk.

These objectives are driven by current business requirements; following the iron ore boom and a return to a more sustainable, long-term iron ore price and demand, RTIO is concerned with 'production at the right cost'. However, this focus is still within the context of a business that has ambitious production targets, requiring high equipment reliability and an ongoing commitment to HSE excellence.

## 3.4 Analysis level and engine subsystems defined

The engine subsystem level has been chosen as the analysis level, to align with section 2.5.1 (Smith & Hinchcliffe 2003, pg. 75-76).

The following engine subsystems have been grouped according to GE Transportation training manuals (GE Transportation 2012*a*). Where there are interfaces between systems (i.e. the turbocharger interfaces with the combustion and exhaust air systems and the intercooler interfaces with the combustion air and cooling systems), the component is grouped in the system if the component's primary function supports the system's function(s). For example, the turbocharger supports the combustion air system's function to supply combustion air at a specified pressure and flow rate, so it is considered part of the combustion air system and not the exhaust system (Smith & Hinchcliffe 2003, pg. 82-86).

### Bottom End

The bottom end includes:

- The engine mainframe (block)
- Crankshaft
- Camshafts and drive/idler gear
- Crankshaft and camshaft bearings
- Engine oil pan
- Integrated front end cover

### Fuel System

The Fuel System includes:

- Fuel tank
- Fuel lines
- Low pressure fuel transfer pump
- Fuel filter assembly
- High pressure fuel pump, line and injector
- Regulating valve
  (The regulating valve provides back pressure in the return fuel lines.)

### Engine Sensors

The GEVO engine features more sensors than is reasonable to list. Some of the most important sensors are:

- ECU - Engine Control Unit
- Engine fuel pressure sensor
- Crank speed sensors 1 and 2
- Fuel management sensor inputs, including:
  - Manifold Air Pressure (MAP)
  - Manifold Air Temperature (MAT)
  - Barometric Pressure (BAP)
- Engine protection sensor inputs, including:
  - Engine water inlet/outlet temperature (EWIT/EWOT)
  - Engine oil inlet/outlet temperature (ELIT/ELOT)
  - Ambient True Temperature (turbo inlet) (ATT)
  - Pre-turbo right temperature (PTRT)
  - Pre-turbo left temperature (PTLT)
  - Engine water inlet/outlet pressure (EWIP/EWOP)
  - Engine Oil inlet/outlet pressure (ELIP)
  - Crankcase overpressure sensor (COP)
  - Fuel supply pressure (EFP)
  - Turbo speed sensor

### Long Power Assembly

The Long Power Assembly includes:

- Cylinder head and strongback

- Piston assembly and connecting rod
- Big end bearings
- Cylinder liner
- Valve train and pushrods

### Lubricating Oil System

- Pre-Lubricating pump
- Lubricating oil pump
- Oil filters
- Oil cooler
- Oil pipes

### Cooling System

- Water pump
- Water storage tank
- Radiators
- Radiator fans
- Water discharge manifold

### Combustion Air

- V-screens
- Plastic air cleaner panels
- Baggy air filters
- Turbocharger
- Water-based intercooler

- Air-based intercooler
- Air ducts

#### Exhaust Air

- Exhaust manifold
- Exhaust stack

## 3.5 Subsystem prioritisation

The performance of each engine subsystem has been assessed against the criteria set out below, as recommended by Smith & Hinchcliffe (2003, pg. 77) and Standards Australia (2011, pg. 15-16).

Extracts of the source data for this prioritisation analysis can be found in appendix B.

**Health, Safety and Environmental (HSE)** is a vital measure of equipment performance; RTIO's license to operate requires adherence to HSE regulations.

**Corrective maintenance** has been divided into:

- **PM02 events**, which describe maintenance events that are able to be planned and prepared for, but are not scheduled maintenance. Generally, this describes two types of maintenance events:
  - Potential failures that are detected while on the P-F curve; the equipment has not yet failed but is showing signs of impending functional failure. Condition-based maintenance activities are PM02 events.
  - Fleet-wide modifications and upgrades.
- **PM03 events**, which are genuine break-down events, are reserved for functional failures.

The two events are fundamentally different by definition and have a profoundly different impact on the railway network; this is primarily determined by the planned, prepared nature of the PM02 orders versus the unplanned, disruptive effect of PM03 events. For this reason, the PM03 event count has a greater impact than the PM02 event count. As such, this analysis has treated the two categories separately in addition to an analysis of total costs.

The first sample of raw corrective maintenance data collected contained approximately 5000 entries. To process the raw data into useable data, the author used a spreadsheet word search function to extract and categorise work orders. Any work orders that were not sorted in this fashion were manually examined. Refer to section B for example raw data.

**Network Delay Data** is a measure of the impact of failures on production and a close equivalent to equipment downtime. Many failures translate to lost business output, having a serious effect on the supply chain as a whole.

The network delay data includes a relatively large unknown category. This is due to intermittent faults that are not easily resolved and difficulties collecting data from the field.

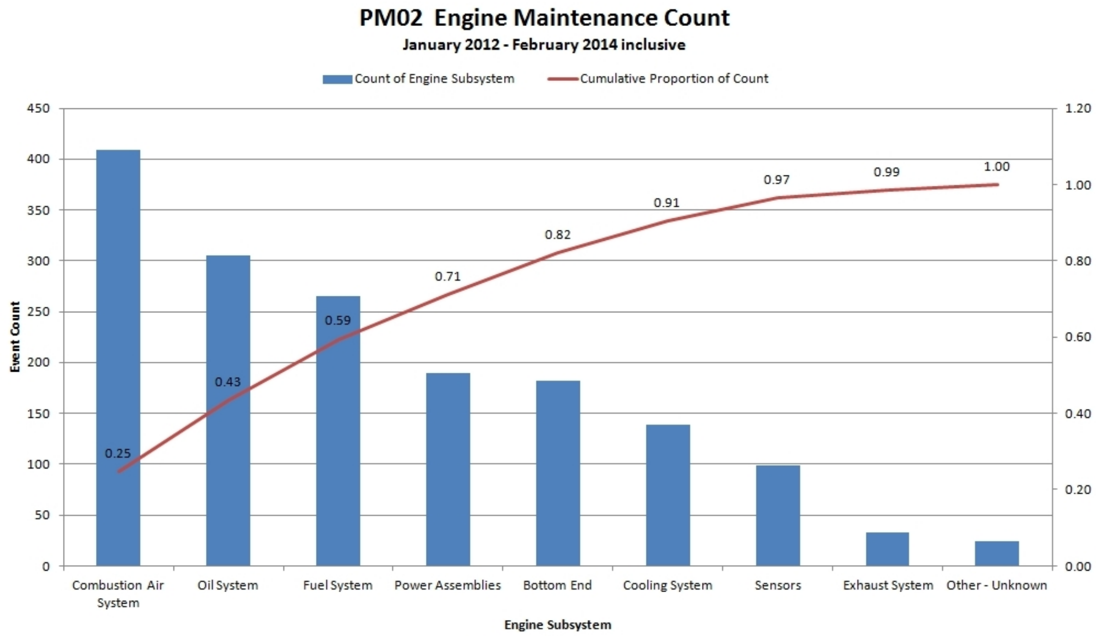
The network delay data was sorted in the same manner as the corrective maintenance data. Refer to section B for an example of raw data.

Primary maintenance (PM01) has not been considered in the analysis. PM01 maintenance is generally completed against a work order that is built at the locomotive level, not the engine or engine system level. The effort required to determine the costs and labour associated with each engine subsystem is considered unnecessary and prohibitive.

### 3.5.1 Corrective Maintenance - PM02 Data

Power assemblies are the driver behind PM02 maintenance expenses, followed by the combustion air system, forming the top two and top 80% of maintenance expenses (refer to figure 3.1).

The event count reveals different drivers and a more even spread; the combustion air system, oil system, fuel system, power assemblies and bottom end make up the top five and 80% of events (figure 3.1). The event count does not conform neatly to the Pareto Principle, but still provides an indication of where the best return on investment will lie.



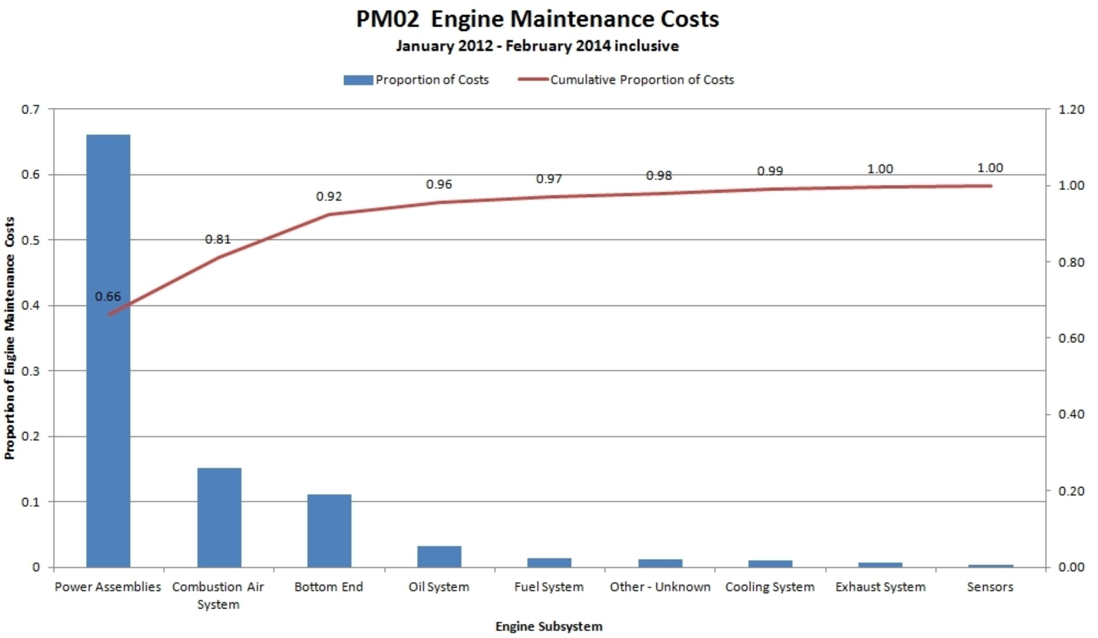




Figure 3.1: Pareto of PM02 Count and Cost Data

### 3.5.2 Corrective Maintenance - PM03 Data

Figure 3.2 shows that the power assemblies subsystem and the combustion air subsystem clearly lead the cost of PM03 maintenance, followed by the Fuel system to make up the top three subsystems and round out the top 80% of costs.

Figure 3.2 shows the event count, again revealing different drivers and a more even spread. The oil system, power assemblies, fuel system, combustion air and sensor systems make up the top five and 80% of events. As discussed earlier, the event count of PM03 maintenance indicates a level of disruptiveness to the business, but is not directly quantifiable.

### 3.5.3 Corrective Maintenance - Combined Costs

The combined costs of corrective maintenance include all PMO2 and PMO3 work order data and is shown in figure 3.3. Power assemblies and combustion air systems are clearly the most significant systems and make up the top 80% of the total corrective maintenance spend.

### 3.5.4 Network Delay Data

The network delay data displays a reasonably even spread in figure 3.4. Sensors, fuel system, unknown, cooling system and combustion air system make up the top 80% of the delay duration. In the delay count, the order is slightly different, but the same subsystems are included in the top 80% here as well, indicating correlation between delay count and total duration of network delay.

### 3.5.5 Health, Safety and Environmental Incident Data

The worst performers in terms of HSE are the oil system, fuel system, power assemblies and combustion air systems (refer to figure 3.5). It should be noted that the majority of oil system environmental incidents are due to a design flaw - victaulic pipe couplings have been used to connect lubricating oil pipe work, which then suffers cracking, causing

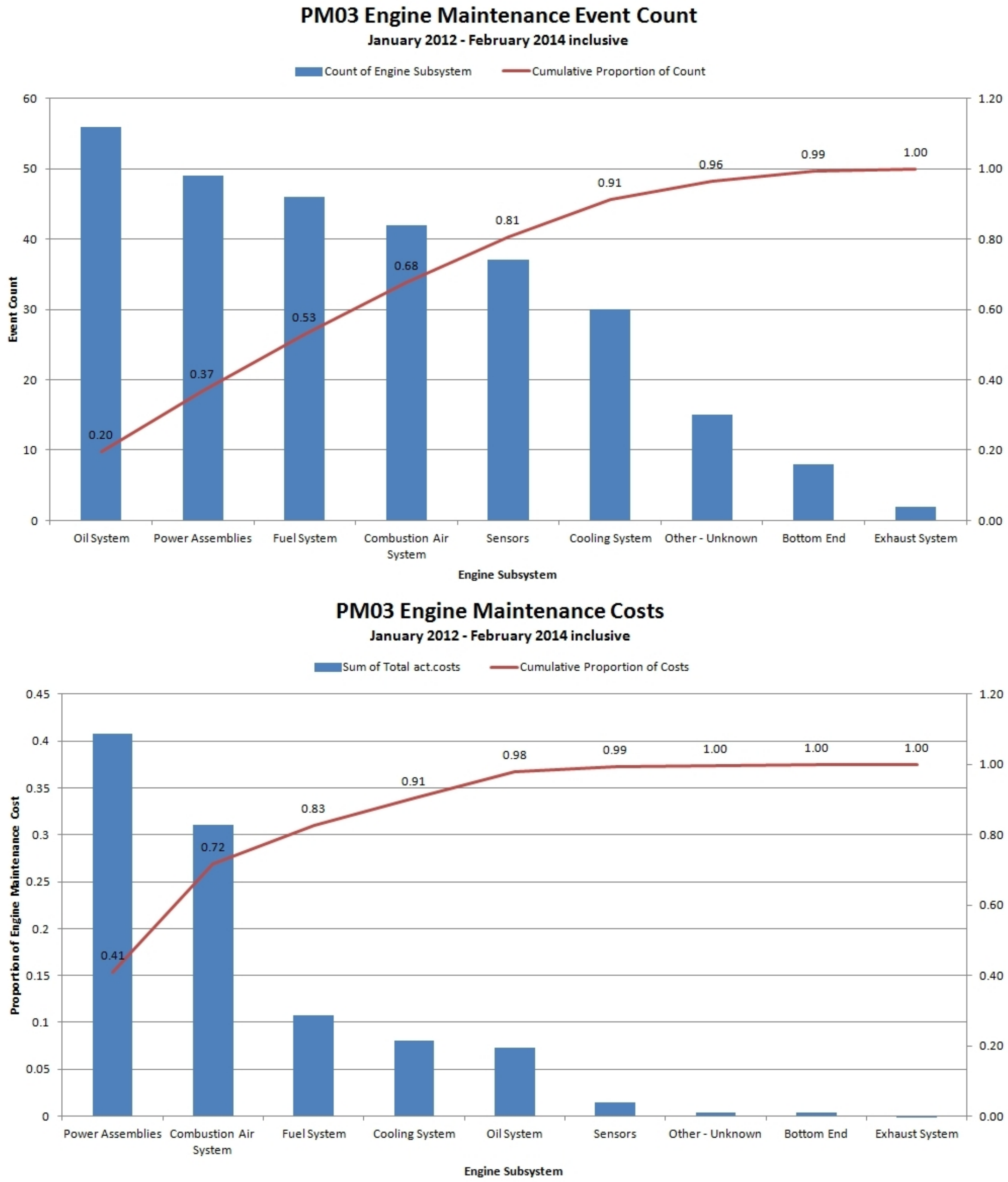



Figure 3.2: Pareto of PM03 Count and Cost Data

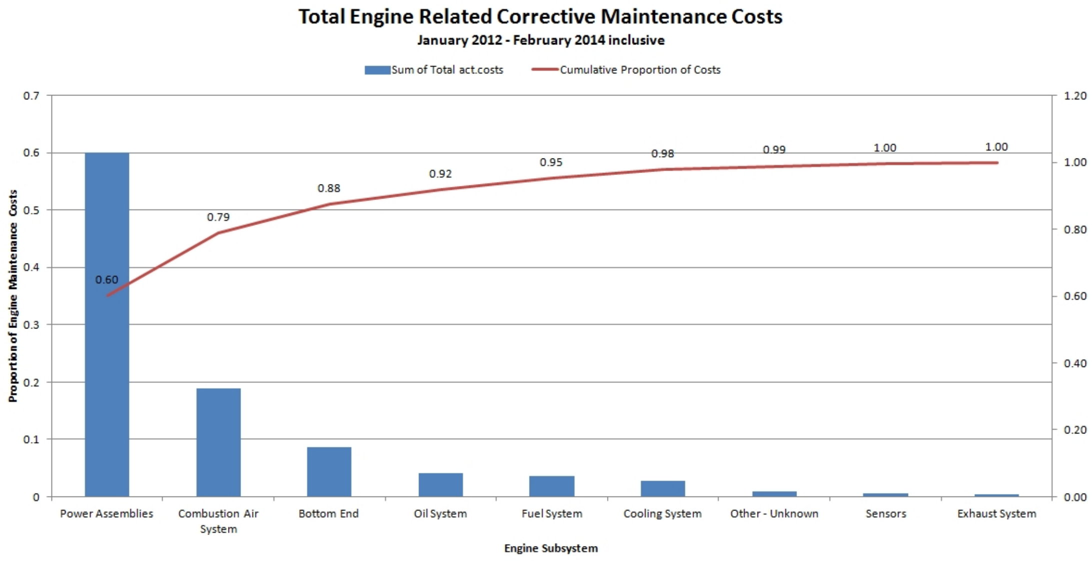



Figure 3.3: Pareto of Combined Cost Data

oil leaks. This component is being redesigned as a flexible pipe, which is expected to solve the problem.

The oil and fuel subsystems both have a maximum incident severity rating of two, or 'medium', as seen in figure 3.5. In particular, the fuel subsystem has two incidents rated as 'medium'.

### 3.5.6 Subsystem Prioritisation Summary

The subsystems are analysed in the following order:

1. The fuel subsystem will be analysed first, for two reasons:
    - It is one of the smaller systems and is expected to provide good analysis material for a 'trial run' of the RCM process.
    - It is in the top two for RDAS delay data and HSE delay data, and in the top three for PM03 data.
2. The Power Assemblies subsystem incurs the greatest costs in both PM02 and PM03 work orders. As stated in section 3.3, cost reduction is a primary objective of this project. Additionally, the Power Assemblies have caused HSE incidents.
3. The Combustion Air subsystem incurs the second greatest maintenance costs, is

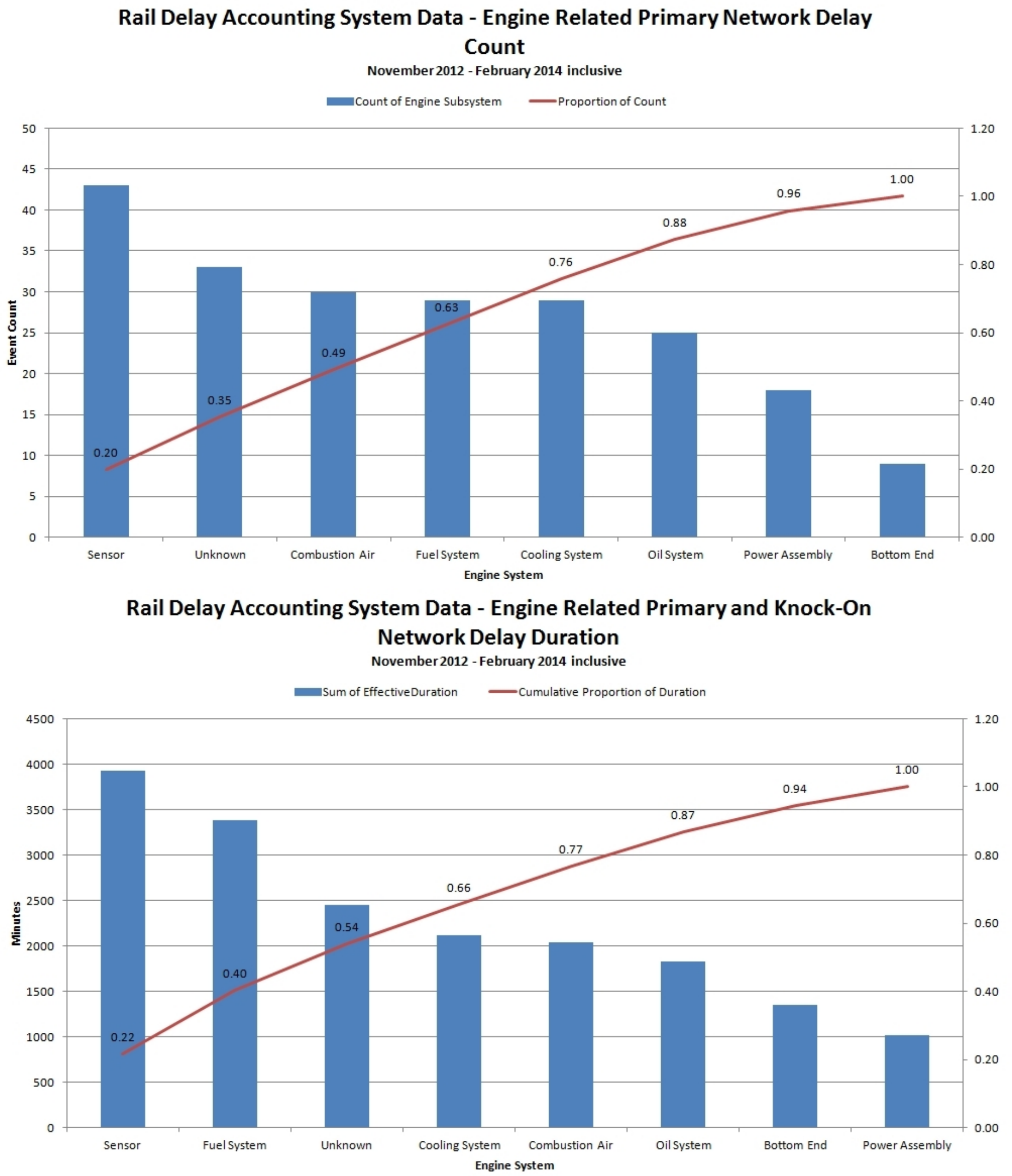
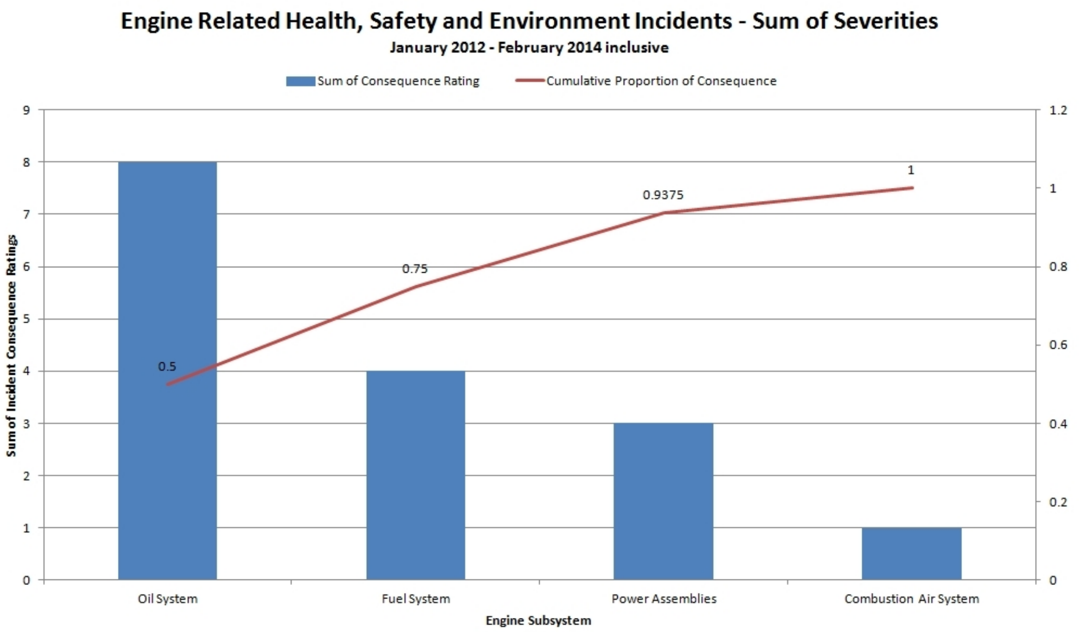



Figure 3.4: Pareto of Network Delay Duration Data

| Engine Subsystem | Maximum Incident Severity |
|---|---|
| Oil System | 2 |
| Fuel System | 1 |
| Power Assemblies | 2 |
| Combustion Air System | 1 |



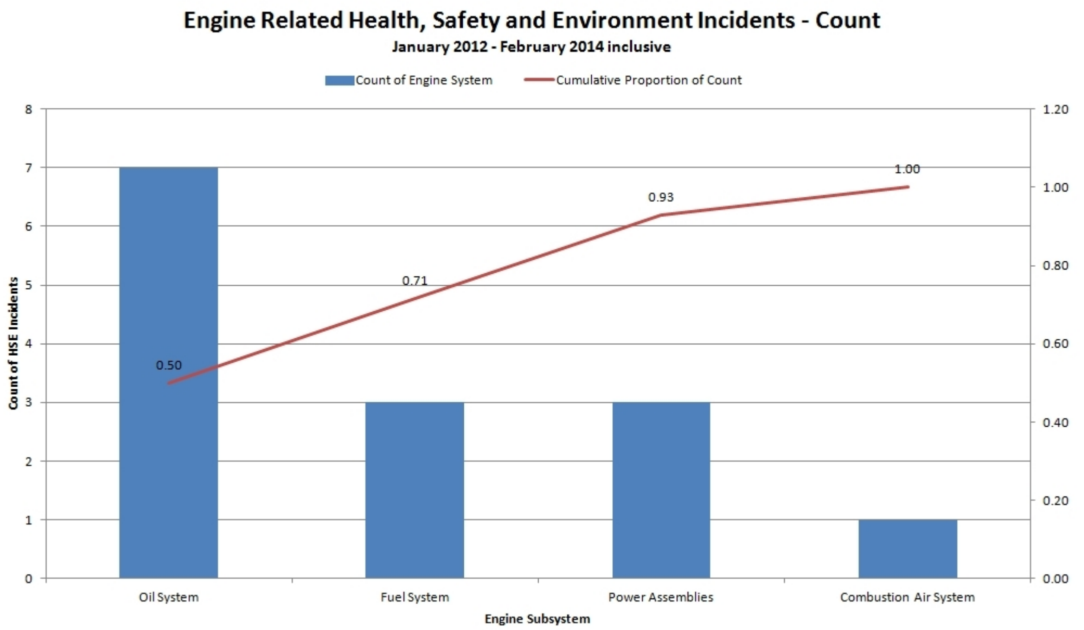




Figure 3.5: Health, Safety and Environmental Incident Severity Rating Data, including maximum severity rating (top), a pareto chart of the sum of the severity ratings (middle) and a pareto chart of the incident count (bottom)

fourth worst for HSE incidents, and is included in the top 80% for network delay duration; it will be prioritised as the third subsystem to be studied.

## 3.6 Operating Context

The operating context statement has been developed according to the method presented by Moubray (2001, pg. 28-35) and Standards Australia (2011, pg. 17-18).

**Business and economic context.** RTIO is currently expanding iron ore production, with ambitious production targets and an optimised, balanced supply chain. Iron ore prices have been high for a number of years but appear to be returning to more sustainable, long-term levels. As such, the business is placing focus on production cost efficiency.

The market demand for iron ore is high; all product can be sold and any lost production time at critical system bottlenecks (e.g. ore car dumpers, ship loaders) directly translates to lost revenue. Delays are estimated by RTIO Business Analysts to incur a cost of $50/minute in most locations (McArthur, J 2014, pers. comm. 6 March).

Iron ore supply to the rail system from the mine is generally consistent. Rail has been considered to be the supply chain bottleneck, because ore supply from the mines generally exceeds the rail capacity. However, the bottleneck location tends to move depending on a number of factors, indicating that the network is optimised and balanced.

The Rail division operates a fleet of 182 locomotives, of which 106 are the EVO model. At any one time, the maintenance department has an allowance for twelve locomotives out of service for maintenance. It is often logistically difficult to remove a locomotive from service for maintenance.

**HSE standards.** RTIO operates with a ‘zero harm’ culture, and no HSE incidents are acceptable. The railway easement passes through national parks and adjacent to culturally sensitive Aboriginal sites, adding an extra layer of responsibility to environmental standards.

**Climate.** The locomotives are operated in the Pilbara region of Western Australia, which is known for long summers that deliver periods of intense heat, approaching 50 degrees Celsius. There is little rain, except during cyclonic events.

**Operation.** The trip from the port to the mine and back to port averages approximately 38 hours and the locomotive will cover between 540 and 860 kilometres depending on the mine location. The locomotive is available for service 24 hours a day, but the asset is not utilised continuously. Precise asset utilisation data is not available.

**Performance.** The Evolution engine is designed to produce 3,300kW of mechanical power, and is operated at this level for a number of hours at a time. The scheduled engine life is 33,750MWhrs (approximately 8 years).

**Redundancy.** The locomotives are usually operated in consists of three, though only two are required for most journeys. A number of mines require up to two 'banker' locomotives to increase tractive effort, and power, while climbing the relatively steep gradients away from the mine. Operating the locomotives in a triple consist reduces the stress on each locomotive and adds redundancy as two locomotives are sufficient to complete most journeys.

'Rescue' locomotives can be sent to recover a failed train, but this is a disruptive action that incurs long network delays. A failed train due to a locomotive shutdown can cause delays of four hours to the network.

**Batch or flow process.** The rail network is technically a batch process, as each train is a batch of ore and if there is a fault, the train can usually be placed on a siding to keep the mainline clear and operational. However, if a crippling failure occurs on single track, the process begins to behave in a flow manner, as the entire network may be blocked.

**Acceptable failure rate.** The maintenance department produces equipment availability and reliability, and the quality of this is primarily measured by the 'successful journey' count. A locomotive is considered to have failed the journey if a fault causes a delay to the rail network. The currently accepted proportion of successful journeys is 95%, so the acceptable failure rate is 1 in 20 for a triple set of locomotives. This may be translated to a failure rate of 1 in 60 trips for each locomotive.

**Time to repair and spare part availability.** Time to repair is dependent upon location. A maintenance technician is located inland at the mines to provide support and can repair a number of locomotive failures, or diagnose the failure so that the workshop can prepare for the repair work ahead of time. Once a locomotive has returned to the workshop, repair time is generally minimal (unless it is a catastrophic failure) as the workshop facility is well equipped with tools and a number of expert troubleshooting maintenance technicians.

Spare part availability is generally good. If a critical spare is not available, it can be transported from Perth (1600km) within three days at a considerable cost, or within one week at normal freight prices.

## 3.7 Regulations and Legislation

Section 2.9 established that there are no regulations or legislation specific to engine maintenance in Australia.

## 3.8 Operating Procedures

Operating procedures are not relevant, as the engine is not operated directly, but is controlled by the Engine Control Unit.

## 3.9 System Boundary Definitions

The subsystem boundary definition follows the template set out in Smith & Hinchcliffe (2003, pg. 85-86). The boundary definition for the fuel system, power assembly system and combustion air system is provided in appendix C.

## 3.10 Fuel system preparatory information and data

Fuel system-specific preparatory data has been gathered as recommended in section 2.5.1 and by Netherton (2002), Rausand (1998), and Standards Australia (2011, pg. 18). The data includes:

- Reliability Analysis
- Safety, incident and accident failure reports
- System BOMs, schematics and technical drawings
- Existing maintenance schedules
- Spare parts usage rates

### 3.10.1 Reliability Analysis

The three major items in the fuel system are the fuel transfer pump, High Pressure (HP) fuel pumps and HP fuel injectors, and the service life data of each of these items has been modelled.

**High Pressure Fuel Pumps**

The HP fuel pumps were modelled as a set consisting of the twelve pumps. The author believed this to be the best method because:

- During primary maintenance, HP fuel pumps are replaced as a set.
- When a locomotive experiences a failed pump, only one component is replaced, but the component position identification is not always recorded, so it is not possible to track failure data for each individual component.

Section 2.7 states that a Weibull plot should be performed on one failure mode only (Abernethy 2006, pg. 1.4). The author investigated each failure to determine the failure mode; however, due to limited detail in the failure data, this is not possible. Where the failure mode was able to be discerned, manufacturing faults that have been corrected were excluded; all other failure modes were included, treating the unit as a black box. The interpretation of the results must bear in mind the limitations in the data.

The pumps can be modelled as a pump-set and, when failures occur, the repair of the set is treated 'as good as old', because only one of the twelve pumps has been replaced (refer to section 2.7) (Meridium 2012).

For an extract of the source data used to model the HP fuel pumps and injectors, refer to figures G.1 and G.2.

A review of maintenance records revealed the following information about HP pump failure modes:

- 3 Due to guide pin falling out (a manufacture defect that has been eliminated)
- 1 Corroded (no further detail available)
- 1 Solenoid not engaging
- 1 Leaking
- 4 Unknown

The author notes that it is unlikely that the 4 unknown failures were due to the manufacturing defect as there was no evidence of components replaced due to secondary damage. When the guide pin falls out, the cam section is damaged.

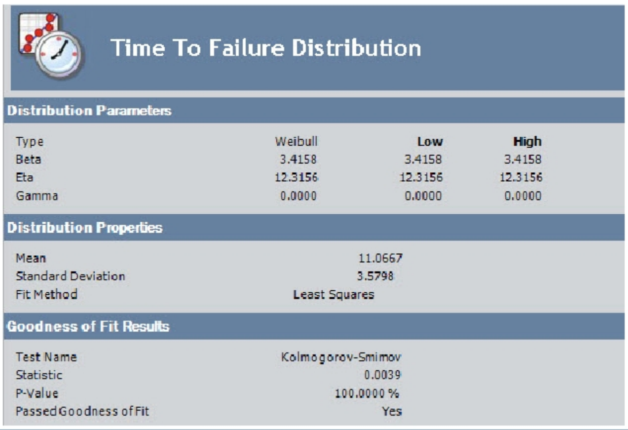
Referring to figure 3.6, the results indicate that the HP fuel pump generally displays a wear-out failure mode ($\beta = 3.42$). Thus the data indicates that extending the pump service life will increase the failure rate.

#### High Pressure Fuel Injectors

The HP Injectors are modelled as a set of twelve, as described for the HP Pumps in section 3.10.1.

No significant detail could be found on the injector failure modes; as described for the HP pumps in section 3.10.1, the injector is modelled as a black box unit.

Referring to figure 3.7, the injectors appear to be most unreliable early in life and their reliability increases with time.



Time To Failure Distribution

**Distribution Parameters**

| | | | |
|---|---|---|---|
| Type | Weibull | **Low** | **High** |
| Beta | 3.4158 | 3.4158 | 3.4158 |
| Eta | 12.3156 | 12.3156 | 12.3156 |
| Gamma | 0.0000 | 0.0000 | 0.0000 |

**Distribution Properties**

| | |
|---|---|
| Mean | 11.0667 |
| Standard Deviation | 3.5798 |
| Fit Method | Least Squares |

**Goodness of Fit Results**

| | |
|---|---|
| Test Name | Kolmogorov-Smirnov |
| Statistic | 0.0039 |
| P-Value | 100.0000 % |
| Passed Goodness of Fit | Yes |

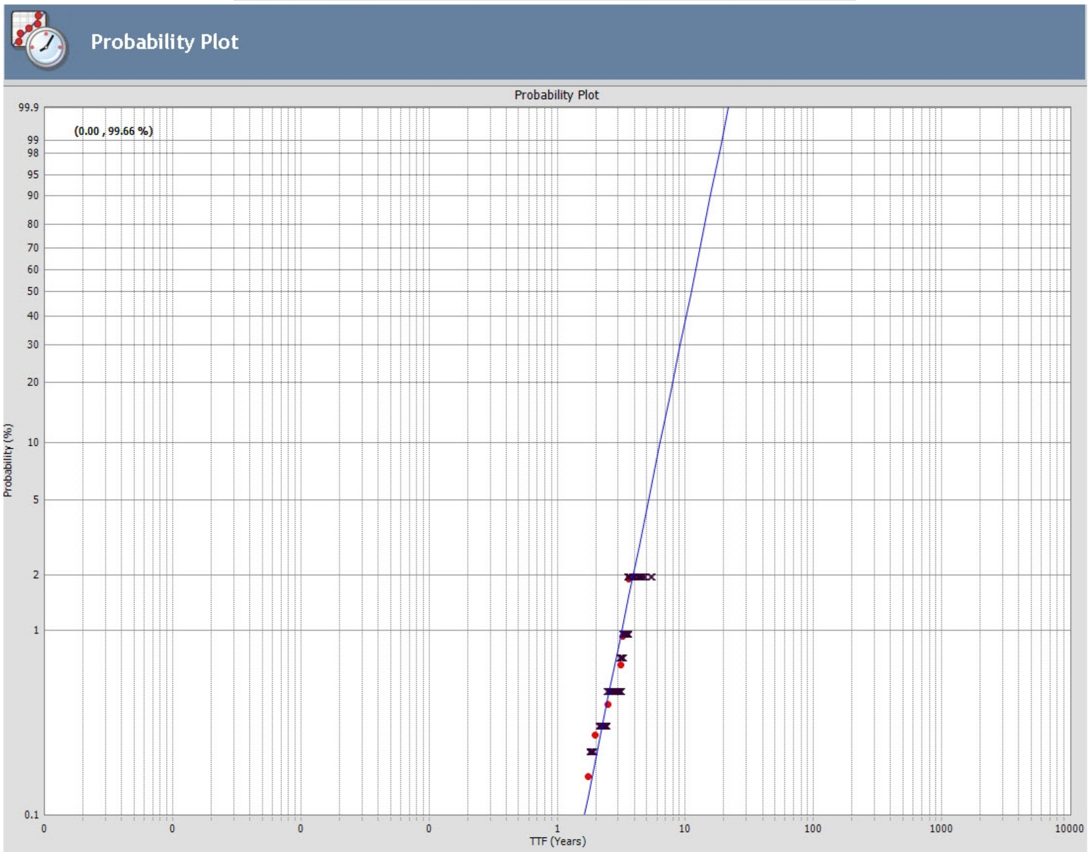



Figure 3.6: High Pressure Pump Weibull Plot

## Time To Failure Distribution

**Distribution Parameters**

| Type | Weibull | Low | High |
|---|---|---|---|
| Beta | 0.8031 | 0.8031 | 0.8031 |
| Eta | 231459.9547 | 231459.9547 | 231459.9547 |
| Gamma | 0.0000 | 0.0000 | 0.0000 |

**Distribution Properties**

| | |
|---|---|
| Mean | 261522.9707 |
| Standard Deviation | 328278.9837 |
| Fit Method | Least Squares |

**Goodness of Fit Results**

| | |
|---|---|
| Test Name | Kolmogorov-Smirnov |
| Statistic | 0.0142 |
| P-Value | 100.0000 % |
| Passed Goodness of Fit | Yes |

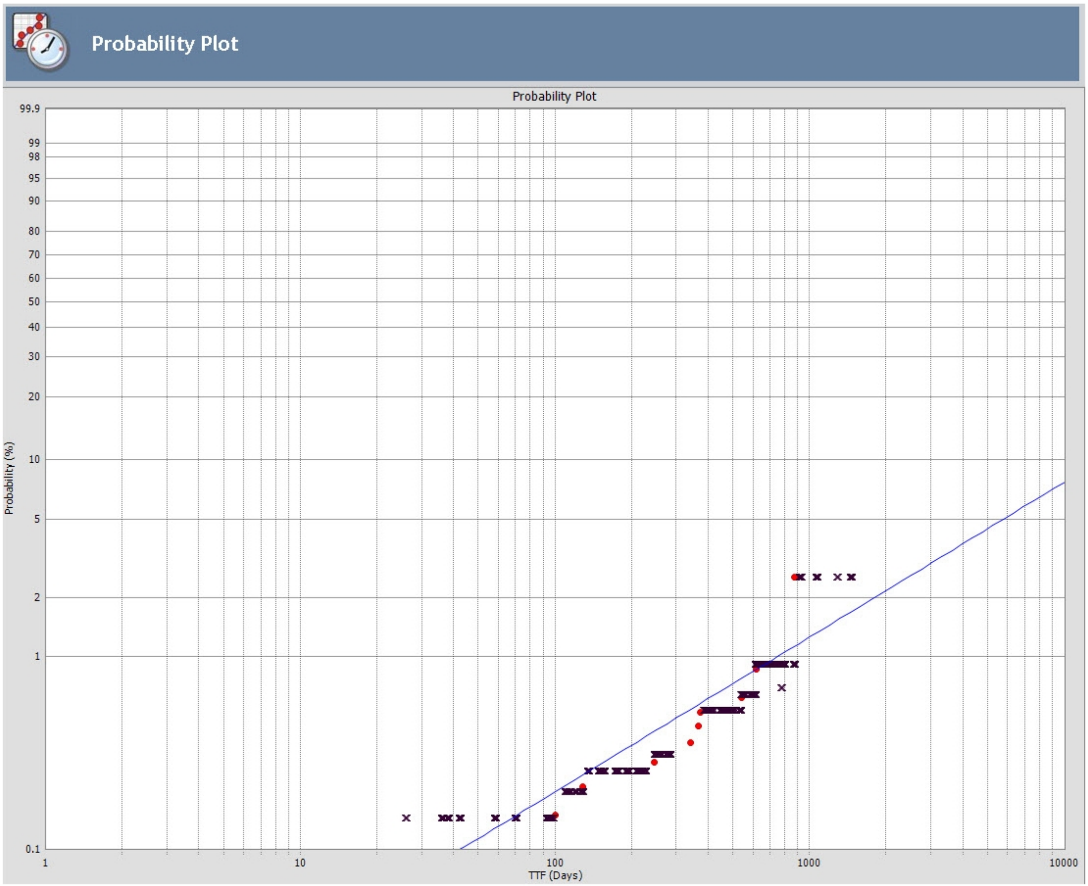
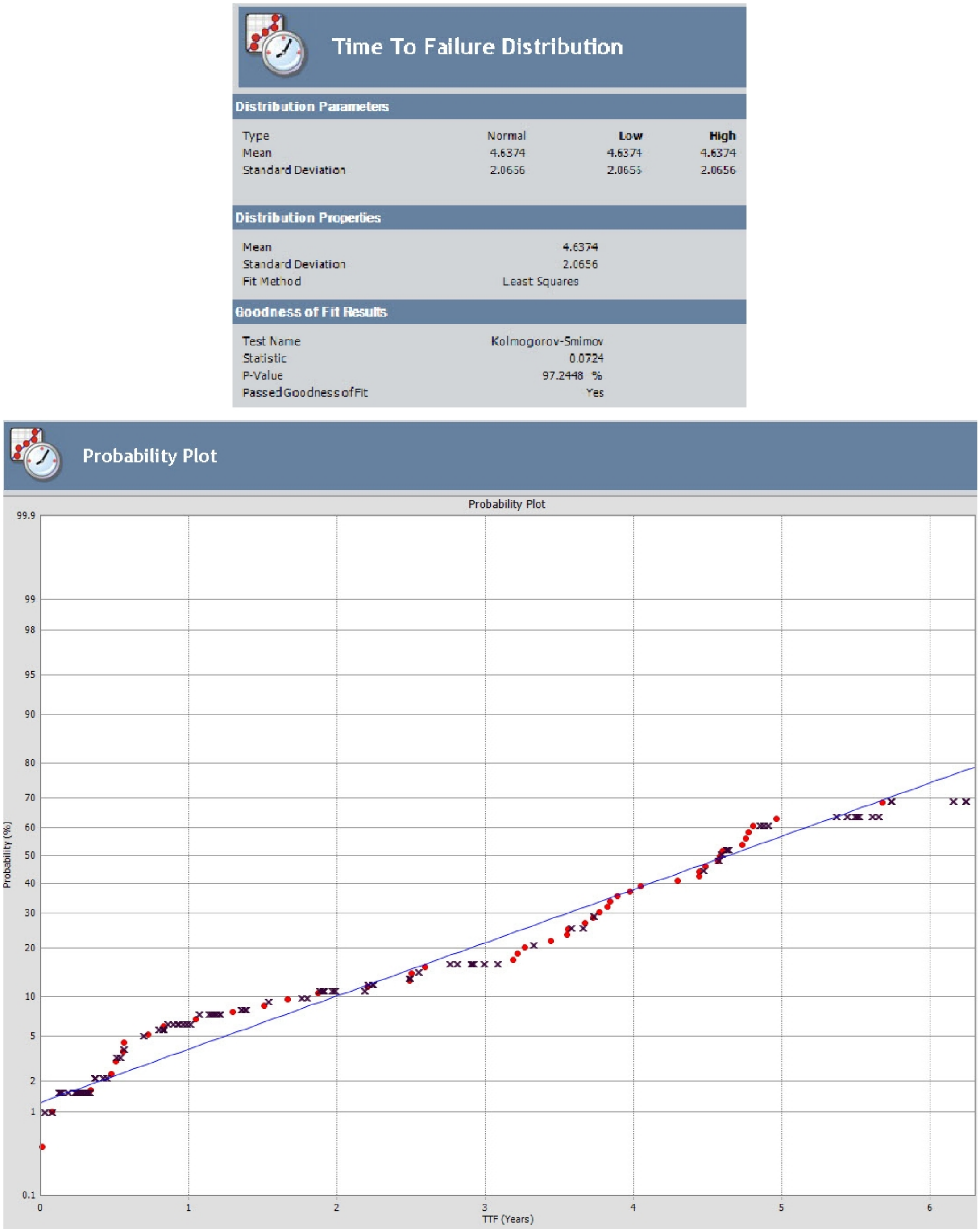



Figure 3.7: High Pressure Injector Weibull Plot



Time To Failure Distribution

**Distribution Parameters**

| | | Low | High |
|---|---|---|---|
| Type | Normal | | |
| Mean | 4.6374 | 4.6374 | 4.6374 |
| Standard Deviation | 2.0656 | 2.0656 | 2.0656 |

**Distribution Properties**

| | |
|---|---|
| Mean | 4.6374 |
| Standard Deviation | 2.0656 |
| Fit Method | Least Squares |

**Goodness of Fit Results**

| | |
|---|---|
| Test Name | Kolmogorov-Smirnov |
| Statistic | 0.0724 |
| P-Value | 97.2448 % |
| Passed Goodness of Fit | Yes |



Figure 3.8: Fuel Transfer Pump Modelling Plot

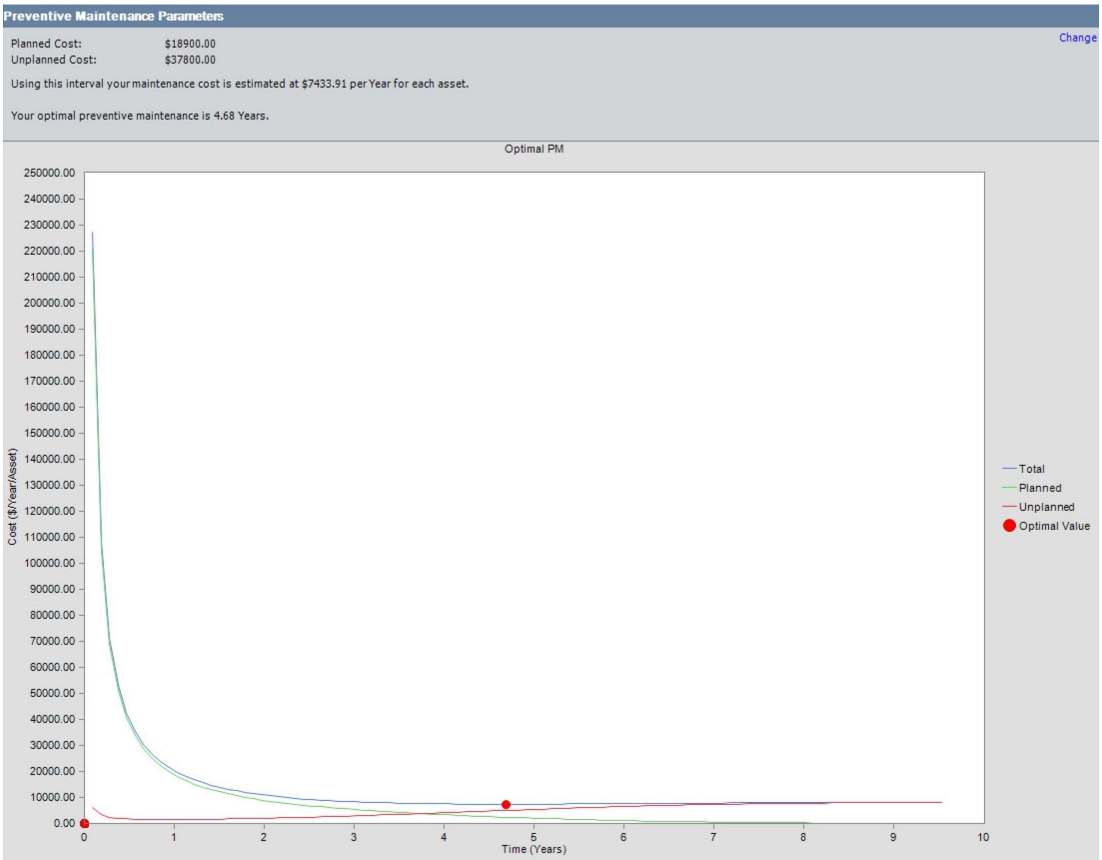



Figure 3.9: Fuel Transfer Pump Modelling - Service Life Optimisation

**Fuel Transfer Pump**

Referring to figure 3.8, it can be seen that the transfer pump is not modelled by the Weibull distribution but the Normal distribution. The fuel transfer pump is currently experiencing failures due to a design flaw that the OEM is taking action to rectify.

An optimisation using RTRS was performed and is displayed in figure 3.9; the optimum replacement period is calculated to be 4.68 years, which most closely aligns with the half engine life of approximately 4 years.

### 3.10.2 Component performance analysis

High Pressure fuel pumps and injectors are identified in the RCM analysis as items that are best maintained by scheduled restoration. To aid evaluation of the correct interval for maintenance, teardown inspections have been carried out on the injectors; HP fuel pumps have not been assessed due to limited availability of spare parts in the rotable

| Summary of general condition observations | |
|---|---|
| Item | Description |
| 1 | High leakage |
| 2 | Nozzle spray holes blocked |
| 3 | Nozzle opening pressures low |
| 4 | Nozzle seats leaking |

Figure 3.10: Fuel system injector performance assessment results summary

| Injector | Chatter Test | Seat Leakage | Spray Pattern | Opening Pressure (bar) (design =450 bar) |
|---|---|---|---|---|
| 1 | Fail | Fail | Fail | 405 |
| 2 | Fail | Fail | Fail | 420 |
| 3 | Fail | Fail | Fail | 408 |
| 4 | Fail | Fail | Fail | 409 |
| 5 | Fail | Fail | Fail | 408 |
| 6 | Pass | Fail | Pass | 408 |
| 7 | Fail | Fail | Fail | 398 |
| 8 | Fail | Fail | Fail | 396 |
| 9 | Fail | Fail | Fail | 398 |
| 10 | Fail | Fail | Fail | 393 |
| 11 | Fail | Fail | Fail | 427 |
| 12 | Fail | Fail | Fail | 428 |

Figure 3.11: Fuel system injector performance assessment results

pool at the time of writing.

The author was unable to locate an Australian Standard to define the test methods; the standard tests conducted by a reputable diesel injection repair workshop were accepted.

### Injector Teardown Analysis and Performance Assessment

A full set of 12 fuel injectors were sent to United Fuel Injection for performance assessment. The results were disappointing; the injector performance was much worse than expected, even for end-of-life.

The key points were noted by the diesel injection workshop:

- 11 of the 12 injectors did not create an acceptable atomised spray pattern. Refer to figure 3.11 for recorded results. Refer to figure 3.12 for an example of a poor injector and the best injector, respectively.
- All injectors suffered excessive back-leakage (refer to figures 3.10 and 3.11).

Figure 3.12: Disassembled injectors (top left), injector displaying blocked nozzles (top right), injector displaying streams of unatomised diesel (bottom left) and a properly performing injector (bottom right)

- The cracking (injector opening) pressures were low, some by as much as 54 bar (refer to figure 3.11).
- A number of nozzles were blocked (refer to figures 3.10 and 3.12).
- A number of injector seats were leaking (figure 3.10).

These results indicate that a life extension on the injectors is not possible at this time; a defect elimination project will be required to determine the root cause of poor injector performance, eliminate the root cause and ensure that the injectors are fit to be operated for the standard service life.

### 3.10.3 Safety, incident and accident failure reports

Figures E.1 and E.2 in appendix E provide the relevant examples from the RTIO HSE incident recording system. The fuel system incidents are due to bolts that are left loose following maintenance.

### 3.10.4 System Bill Of Materials (BOM), technical manuals, schematics and assembly drawings

It is not practical to include the entire technical assembly drawings and BOM, but an extract has been included in appendix D.

A system schematic is included in figure 3.13 and a representation of the HP fuel pump is included in figure 3.14.

### 3.10.5 Existing maintenance program

Scheduled maintenance tasks are currently applied as shown in table 3.1.

### 3.10.6 Spare parts usage rates

A summary of parts usage rates is provided in table 3.2. Further details are provided in appendix F, including a breakdown by monthly usage and scheduled versus unscheduled

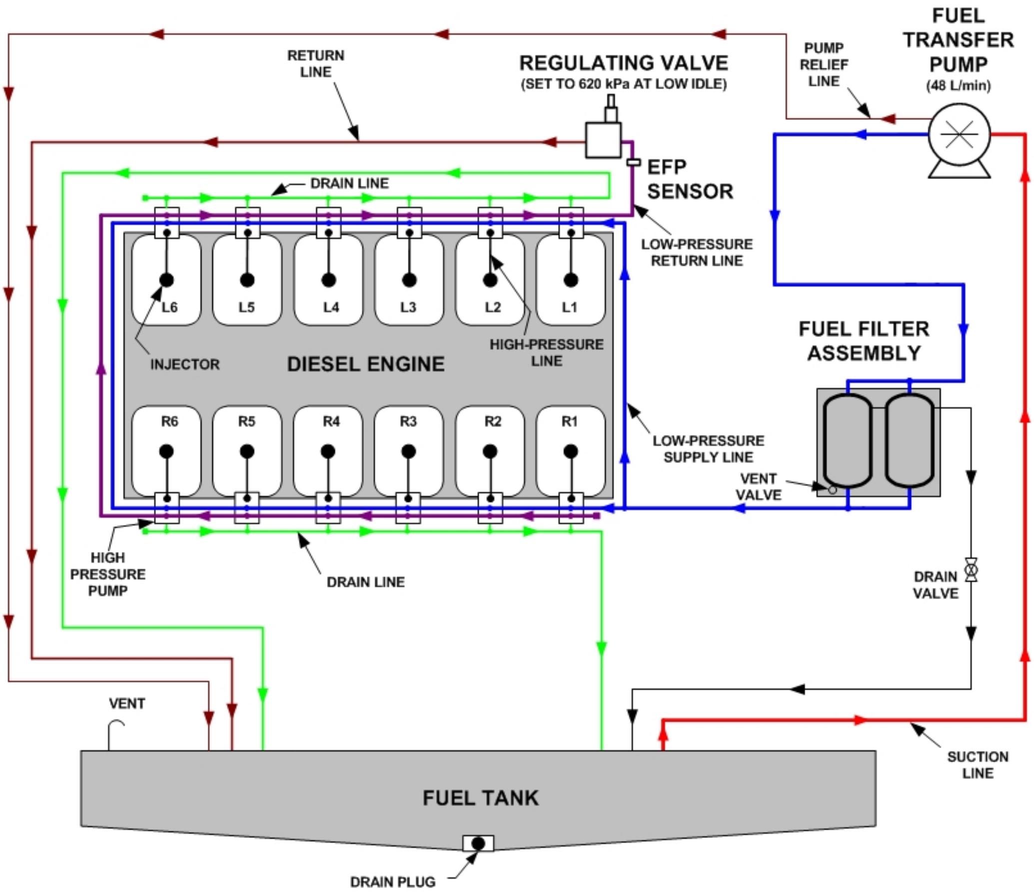



Figure 3.13: Fuel System Schematic (GE Transportation 2012*a*, sec. 5 pg. 4)

Table 3.1: Scheduled maintenance applied to fuel system components

| Item | Scheduled Interval |
|---|---|
| Fuel Transfer Pump replacement | 11,000 MWHrs |
| High Pressure Fuel Pump replacement | 11,000 MWHrs |
| Fuel Injectors replacement | 7,000 MWHrs |
| Fuel Strainer and Seal replacement | 4 Monthly |
| Fuel Filters and Seal replacement | 4 Monthly |
| Dead Cylinder Test | 4 Monthly |
| General inspection for leaks and rubs | Daily and 4 Monthly |
| Low pressure fuel pressure inspection | 4 Monthly |

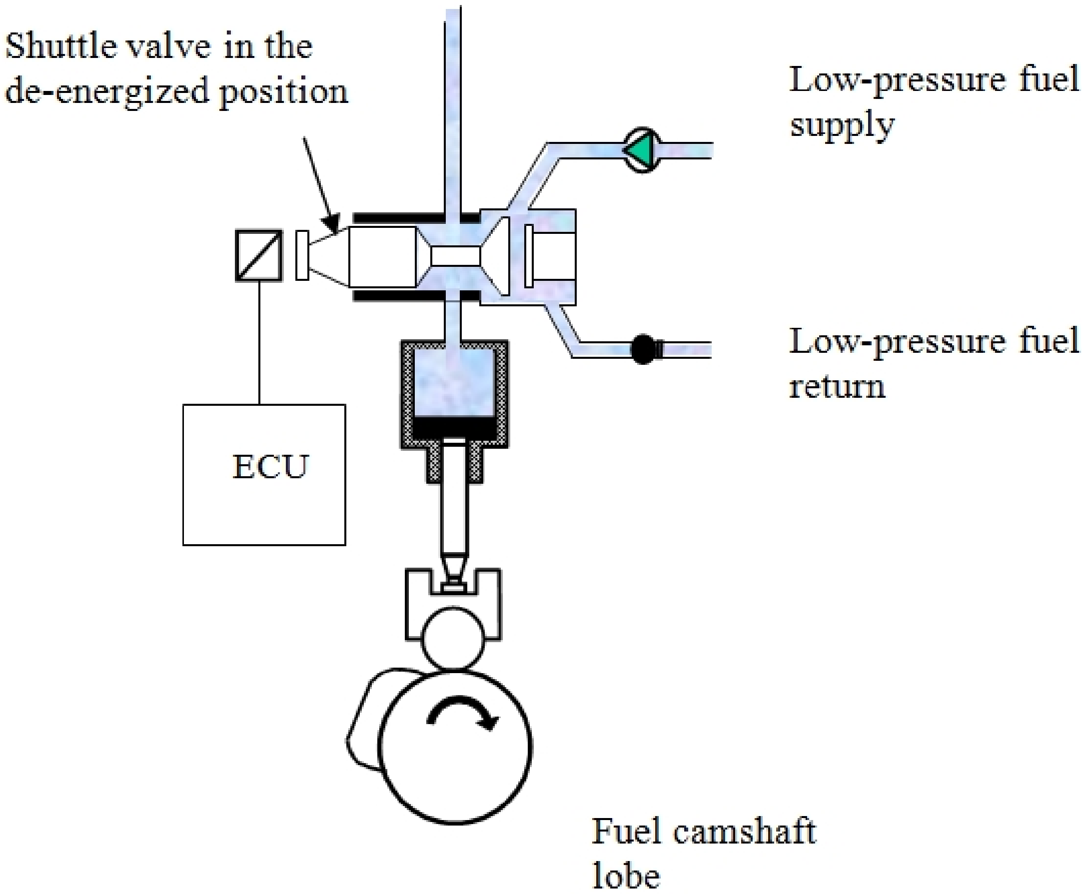



Figure 3.14: Fuel System HP Pump (GE Transportation 2012$a$, sec. 7 pg. 3)

Table 3.2: Total fuel system component consumption, January 2013 to March 2014 - * indicates an estimate, as the item is supplied as part of a service kit, not individually

| Item | Total Component Usage |
|---|---|
| Fuel Transfer Pump | 26 |
| High Pressure Fuel Pump | 207 |
| Fuel Injectors | 642 |
| Fuel Strainer* | 302 |
| Fuel Filters* | 309 |
| Fuel Regulating Cartridge | Nil |
| High Pressure Fuel Line | 1 |

usage.

## 3.11 Power assembly preparatory information and data

The same preparatory data and information has been compiled for the power assembly as for the fuel system (above). For reference, the outline of this data is included at the beginning of section 3.10.

### 3.11.1 Reliability Analysis

Maintenance records indicate that the Evolution locomotives have experienced cracked pushrods five times. Similar to the HP fuel pumps and injectors (reference section 3.10), the pushrods were modelled as a system of 24 components that are repaired 'as good as old'. Figure 3.15 shows that this is a random failure mode ($\beta \approx 1$).

The author was not able to find any other failure modes in the maintenance records that had enough failure data points recorded or warranted investigation. A piston design issue resulted in a large number of premature failures, but it is not considered beneficial to model this data as it is a known design issue that has been eliminated.

| Distribution Parameters | | | |
|---|---|---|---|
| Type | Weibull | Low | High |
| Beta | 0.9362 | 0.9362 | 0.9362 |
| Eta | 2783.0876 | 2783.0876 | 2783.0876 |
| Gamma | 0.0000 | 0.0000 | 0.0000 |

| Distribution Properties | |
|---|---|
| Mean | 2868.6965 |
| Standard Deviation | 3066.2609 |
| Fit Method | Least Squares |

| Goodness of Fit Results | |
|---|---|
| Test Name | Kolmogorov-Smirnov |
| Statistic | 0.0003 |
| P-Value | 100.0000 % |
| Passed Goodness of Fit | Yes |

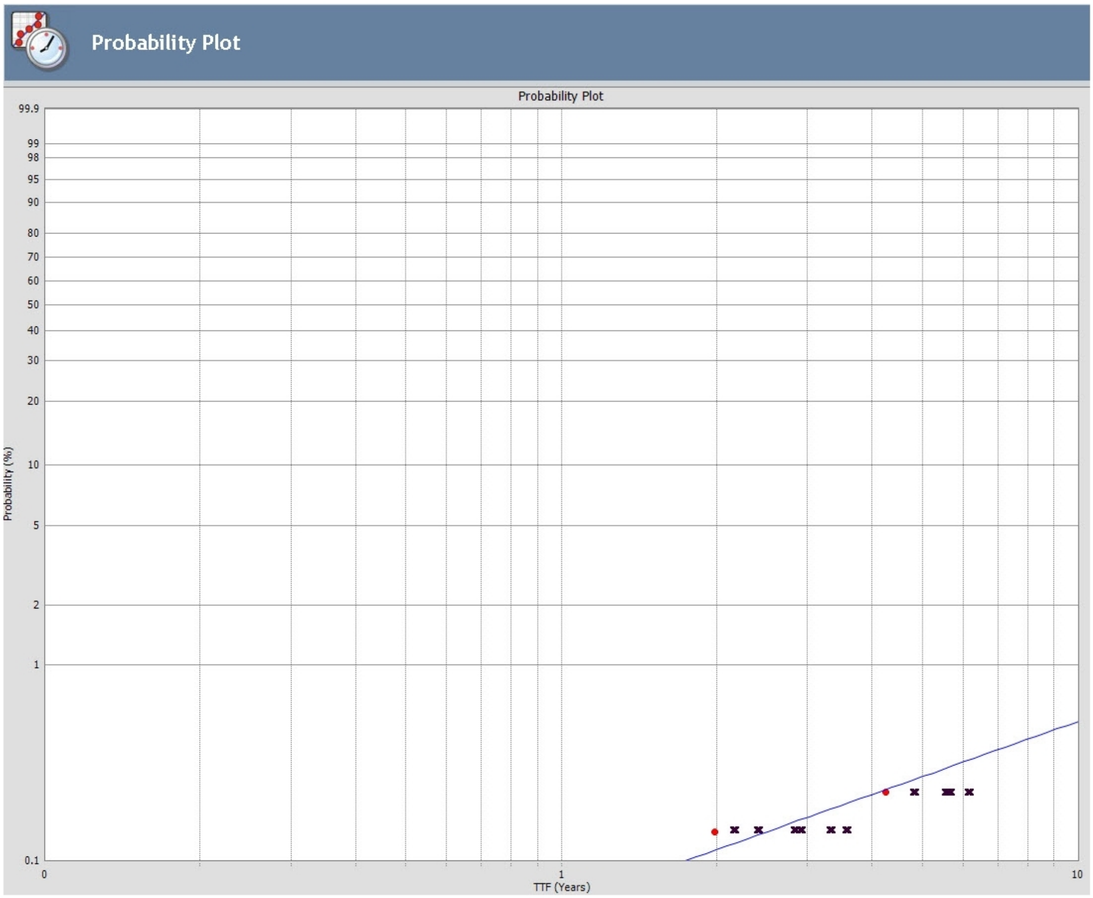



Figure 3.15: Snapped Pushrod Modelling Plot

Table 3.3: Scheduled maintenance items applied to power assembly system components

| Maintenance Item | Scheduled Interval |
|---|---|
| Valve lash inspection and adjustment | 12 Monthly |
| Crosshead and camshaft inspection | 12 Monthly |
| Power assembly overhaul | Engine life - 33,750 MWHrs |

### 3.11.2 Safety, incident and accident failure reports

The power assemblies caused three incidents that were logged in the HSE incident system; each was related to the known piston design issue resulting in a minor oil and/or coolant spill and ranked as a 'low' Maximum Reasonable Outcome (MRO). The power assemblies are not considered to pose a significant risk to safety or the environment.

### 3.11.3 System Bill Of Materials (BOM), technical manuals, schematics and assembly drawings

It is not practical to include the entire technical assembly drawings and BOM, but an extract of the power assembly system drawing showing the primary components is included in figure 3.16. Figure D.4 contains the item number component descriptions.

### 3.11.4 Existing maintenance program

Scheduled maintenance tasks are currently applied as shown in table 3.3. All components are designed to run engine life with only minor inspection or adjustment.

### 3.11.5 Spare parts usage rates

A summary of parts usage rates is provided in appendix F, including a breakdown by monthly usage. All power assembly component usage is unscheduled.

Most items appear to have quite low usage rates; however, four items appear to have excessive consumption. These are displayed in table 3.4.

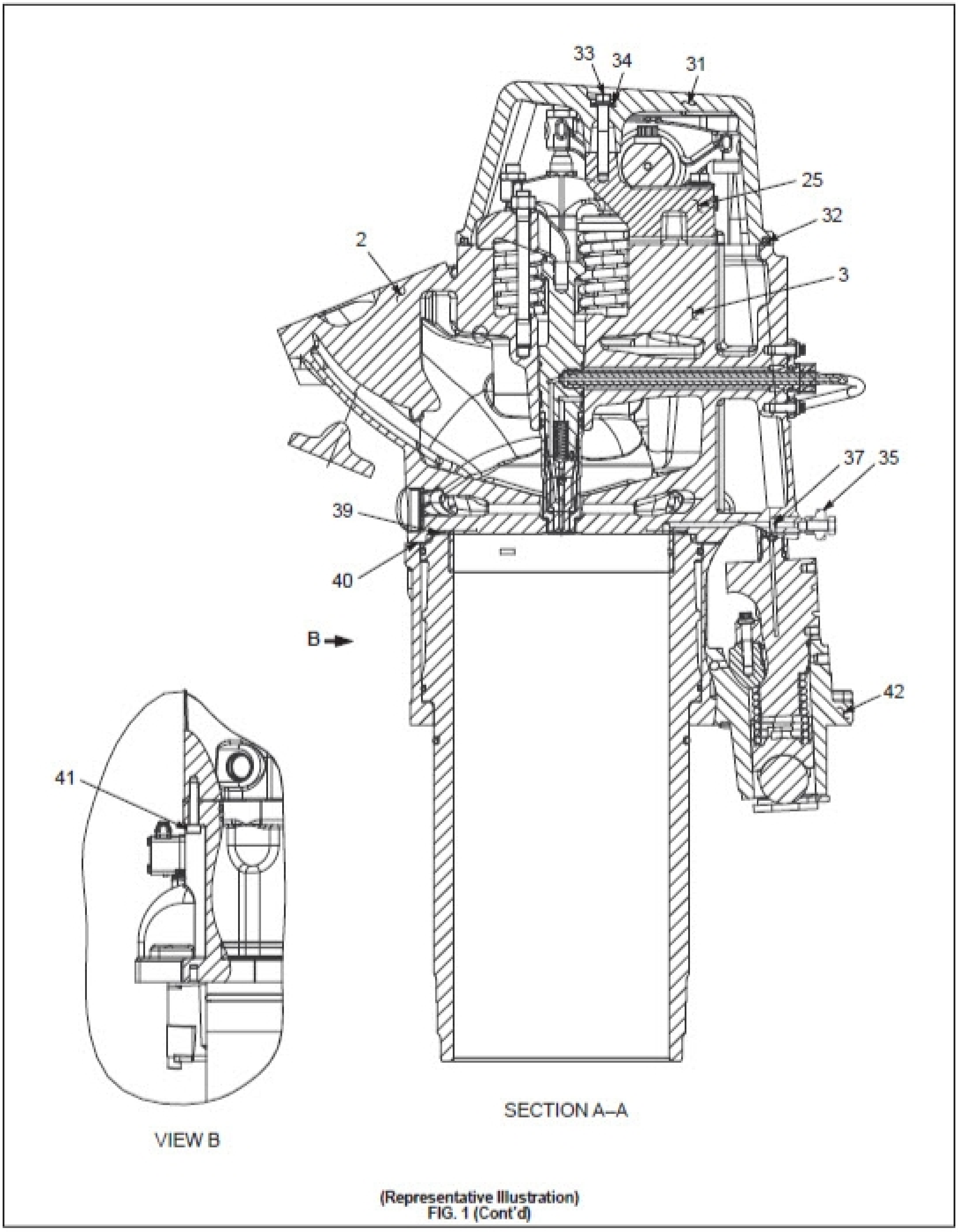



Figure 3.16: Renewal Parts Catalogue Part A - Partial Power Assembly System Bill Of Materials (GE Transportation 2014)

Table 3.4: Total Power Assembly component consumption, January 2013 to March 2014

| Item | Total Component Usage |
|---|---|
| 1. SEAL,O-RING;GE 41A219499ABP246 | 65 |
| 2. POWER ASSY;UPPER;322X1007 | 23 |
| 3. GASKET;STRONG BACK TO TOPDECK,315X1000-2 | 22 |
| 4. RING KIT;PISTON;350X1005 | 16 |

A review of the work orders accompanying the component usage reveals the following;

- Item 1 was largely due to a manufacturer field modification for a separate issue.
- Items 2, 3 and 4 are often replaced together and are mostly accounted for by the piston design issue.

Thus, accounting for special causes, a review of the component usage does not highlight any current or potential reliability problems.

## 3.12 Combustion Air System preparatory information and data

### 3.12.1 Reliability Analysis

During a review of the maintenance history, the author found that the air-to-air intercooler inlet flange had caused a number of failures as a result of fatigue cracking. When the service life data was modelled on the Weibull distribution (3.17), the data indicated that the failure mode had a beta value of 2, indicating increasing probability of failure with age.

### 3.12.2 Safety, incident and accident failure reports

The combustion air system has been responsible for one incident: a turbocharger failure allowed hot pieces of debris to enter the air filter compartment, setting the air filters on fire. The locomotive driver was able to put the fire out with a fire extinguisher.

## Time To Failure Distribution

**Distribution Parameters**

| Type | Weibull | Low | High |
|---|---|---|---|
| Beta | 1.9906 | 1.9906 | 1.9906 |
| Eta | 6.1800 | 6.1800 | 6.1800 |
| Gamma | 0.0000 | 0.0000 | 0.0000 |

**Distribution Properties**

| | |
|---|---|
| Mean | 5.4774 |
| Standard Deviation | 2.8753 |
| Fit Method | Least Squares |

**Goodness of Fit Results**

| | |
|---|---|
| Test Name | Kolmogorov-Smimov |
| Statistic | 0.0746 |
| P-Value | 99.9997 % |
| Passed Goodness of Fit | Yes |

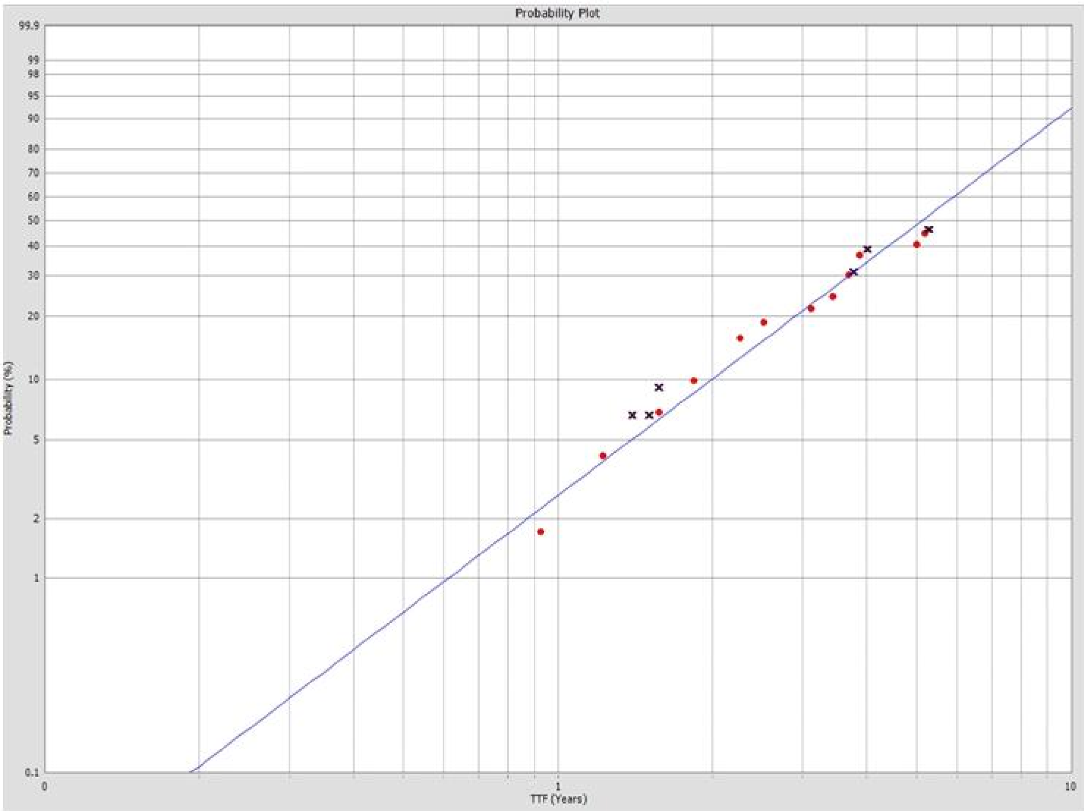



Figure 3.17: Air-to-Air inlet flange fatigue cracking modelled on the Weibull distribution

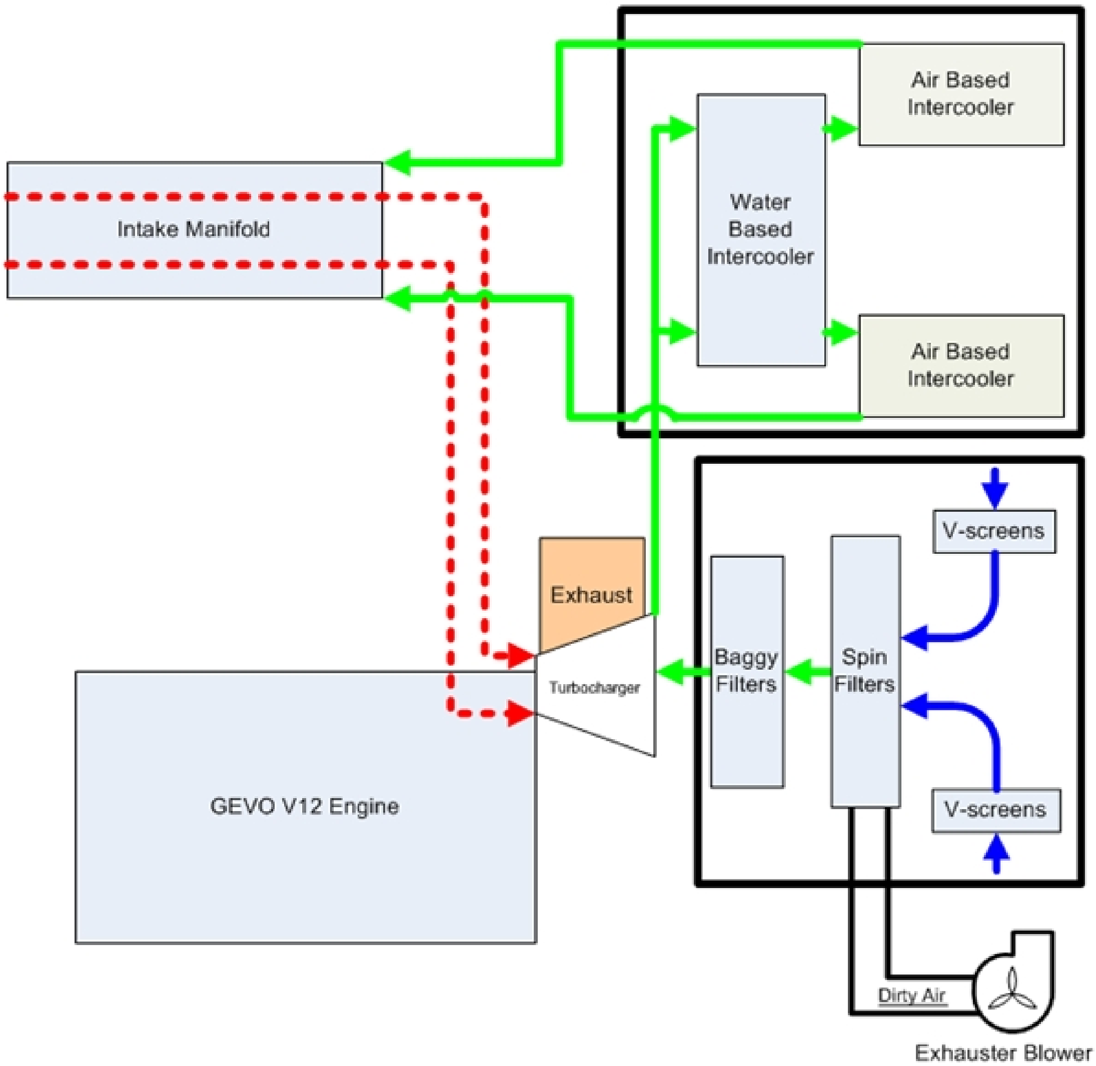



Figure 3.18: Combustion air system schematic

The incident was rated as having low severity due to the small size of the fire and limited amount of combustible material available. As such, the author concludes that the combustion air system is unlikely to cause accidents that have health, safety or environmental ramifications.

### 3.12.3 System Bill Of Materials (BOM), technical manuals, schematics and assembly drawings

A schematic of the combustion air system major components and air flow is included in figure 3.18.

Table 3.5: Scheduled maintenance applied to combustion air system components

| Item | Scheduled Interval |
|---|---|
| Turbocharger | Overhaul at 33,750MWHrs |
| Water based intercooler | Overhaul at 33,750MWHrs |
| Air based intercooler | No current strategy - OEM recommendation: replace at 33,750MWHrs |
| Air based intercooler fans | No current strategy - OEM recommendation: replace at 12 years |
| Spin filters | Wash every 12 months |
| Baggy air filters | Replace every 4 months |

### 3.12.4 Existing maintenance program

The scheduled maintenance currently applied to the combustion air system components is included in table 3.5.

### 3.12.5 Spare parts usage rates

A breakdown of total spare parts consumption rates is included in appendix F, figure F.5. A number of items had a very high rate of usage; each of these were investigated and the findings displayed in figure F.6. Generally the usage was accounted for by large component failures due to manufacturing defects or design flaws, except for the following items that will require further investigation during the analysis:

- O-RING; GE 41A219499ABP374
  - This O-ring is located on the Turbocharger discharge duct. It fails often, but with little consequence. Further details are available in section 6.2.9.
- FLANGE; 8.5"; HEAT EXCH; 84B518058AGP1
  - This flange suffers failure due to fatigue cracking; further discussion is provided in section 6.2.10.

## 3.13 Chapter Summary

This chapter has established the following:

- The required resources and knowledge to complete the RCM.
- The research aims are to understand the maintenance program efficiency; the business objectives are to reduce cost, reduce risk and improve reliability.
- The major engine systems for analysis have been defined and prioritised. The whole engine cannot be analysed due to time constraints, so the systems to be analysed are:
    1. Fuel system
    2. Power Assemblies system
    3. Combustion Air system
- The operating context has been defined.
- Preparatory data specific to each subsystem has been collated and presented.

# Chapter 4

# Reliability-Centered Maintenance Analysis Process

## 4.1 Chapter Overview

This chapter presents the RCM analysis process as undertaken during the project.

The analysis has been developed and recorded in the Rio Tinto Reliability Solution (RTRS). RTRS is based on software commercially available from Meridium Inc. The structure of the software is slightly different to the seven questions asked by the RCM process (Moubray 2001, 16-21); however, all of the required criteria are met to answer these questions in compliance with the JA1011 standard set forth by the Society of Automotive Engineers (2009). It is compliant with the SAE RCM standard JA1011 (Society of Automotive Engineers 2009) (Meridium 2014).

Screen shots from each stage of the RCM software are provided in appendix I.

The fuel system analysis is discussed to provide the reader with an example.

## 4.2 Reliability-Centered Maintenance Analysis Process

### 4.2.1 Fuel System Functions

Following a review of the General Electric Transportation Systems (GETS) training material for the EVO engine and diesel engine theory textbooks (including Mollenhauer & Tschke (2010), Dempsey (2008) and Greuter & Zima (2012)), four functions were identified in the fuel system and defined according to the literature review in section 2.5.3.

Each of the functions and their respective performance parameters are recorded in the 'Function' form in RTRS. For a screenshot of the function data form, refer to figure I.1.

**Fuel System 1. Low Pressure (LP) circuit to contain and provide clean, pressurised fuel to the twelve high pressure fuel pumps.**

This function is a primary and evident function.

GE Transportation (2012*a*, sec. 5, pg. 3-7) specifies the following performance parameters:

- The fuel filters must remove any particles greater than 5 micron in diameter to prevent damage to the HP pumps and injectors that have small component clearances.
- The target supply pressure is 620kPa at low idle; this reduces to 420kPa at maximum engine power production (3310 kW at 1050 rpm, Notch 8).
- The supply pressure must not exceed 896kPa.
- The fuel is supplied at a rate of 48L/min and excess fuel is returned to the tank via the low pressure fuel return line and the high pressure leak-off line.
- The fuel temperature is to be between 17 and 49 degrees Celsius.

**Fuel System 2. HP fuel pumps to provide pressurised, timed, metered fuel to the injectors.**

This function is a primary and evident function.

The HP pump is naturally responsible for providing pressurised fuel to the injectors, but they are also tasked with timing the fuel delivery and metering the amount of fuel that is delivered. This is accomplished using a solenoid that is controlled by the Electronic Control Unit (ECU) (refer to figure 3.14).

The following performance parameters are identified:

- Maximum injection pressure: 1800 bar.
- Notch 8 Injection timing: 5 degrees Before Top Dead Centre (BTDC).

(GE Transportation 2012*a*, sec. 7 pg. 2-5)

**Fuel System 3. HP fuel injectors to supply the metered fuel to the cylinder in the designed spray pattern, in an atomised state.**

This function is a primary and evident function.

The EVO engine spray pattern details are not available, so the author has referenced to general injector theory. A diesel injector must atomise the diesel to facilitate complete combustion (Mollenhauer & Tschke 2010, pg. 64). The function statement implies that leakage and cylinder wall contact is unacceptable, as leaked fuel is not in an atomised state and cylinder wall contact is not part of the designed injector spray pattern (Dempsey 2008, pg. 78).

The only performance parameter identified is that injector needle lift is designed to occur at 450 bar (GE Transportation 2012*a*, sec. 7 pg. 5).

**Fuel System 4. HP fuel to bleed off past pump internal seals, lubricate HP components and drain back to the fuel tank.**

Lubrication of HP fuel system components is an evident, secondary function that is critical to system operation.

### 4.2.2 Functional Failures

The functional failures of the fuel system are defined according to section 2.5.4. An example of the entry form is included in figure I.2. To provide an example, function 2 of the fuel system (described above) can fail in the following ways:

1. Complete HP fuel pump failure - supplies no fuel.
2. Partial failure of HP fuel pump, delivers fuel but does not time or meter fuel appropriately, or supplies fuel below required pressure.
3. Fails to contain fuel.

### 4.2.3 Failure Modes and Effects Analysis (FMEA)

In order to develop the FMEA portion of the RCM analysis as described in sections 2.5.5 and 2.5.6, four primary sources of information were consulted:

- Maintenance records
- Engine maintenance and failure analysis textbooks
- Academic failure analysis papers
- Senior locomotive maintainers

Each of the resources listed above have proved invaluable. A review of the maintenance records allowed the author to glean basic information on common failures seen in the RTIO fleet. A literature review on engine maintenance and failure analysis allowed the author to identify failure modes that have not been witnessed in the RTIO locomotive fleet but are likely to occur if no maintenance were to be performed.

Once the appropriate base level of knowledge was established and the framework for the Failure Modes and Effects Analysis (FMEA) was constructed, an FMEA session was held with senior locomotive maintainers to capture first-hand details and knowledge of RTIO's operation.

The FMEA entry forms are provided in figures I.3, I.4 and I.5.

A relevant example of a failure mode and its effect is:

- 02.01.01 High pressure pump seizes

  - Failure mode details:
    The HP Pump seizes due to wear, cavitation or corrosion over an extended period of time in service, leading to fatigue cracking, material liberation. This gives rise to galling, scuffing and cracking which once initiated, quickly causes the pump to seize.
    This failure mode is a wear-out failure mode. The reliability analysis conducted indicates that the fuel pumps exhibit a strong wear-out pattern ($beta = 3.45$), as presented in section 3.10 and appendix G. Because the failure modes are unknown, it is not possible to know the exact Weibull shape coefficient of this failure mode but it does provide an indication that wear-out failure modes such as this are dominant.
  - Failure effect details:

    * Failure evidence: This failure mode may result in locomotive de-rating, but in most cases the locomotive will overload other power assemblies and continue making full horsepower. The failure may be detected by hearing the cylinder missing, but is most likely to be detected on a Pop test or Dead Cylinder test.
    * Safety and environmental consequences: Nil.
    * Secondary Damage: The most likely case is that the pump seizes at the top of its stroke and no further damage is caused. In the worst possible case, the pump may seize at the bottom of its stroke and push the pump off its mount, snapping the bolts, cracking the high pressure line and wrecking the power assembly, requiring power assembly replacement.

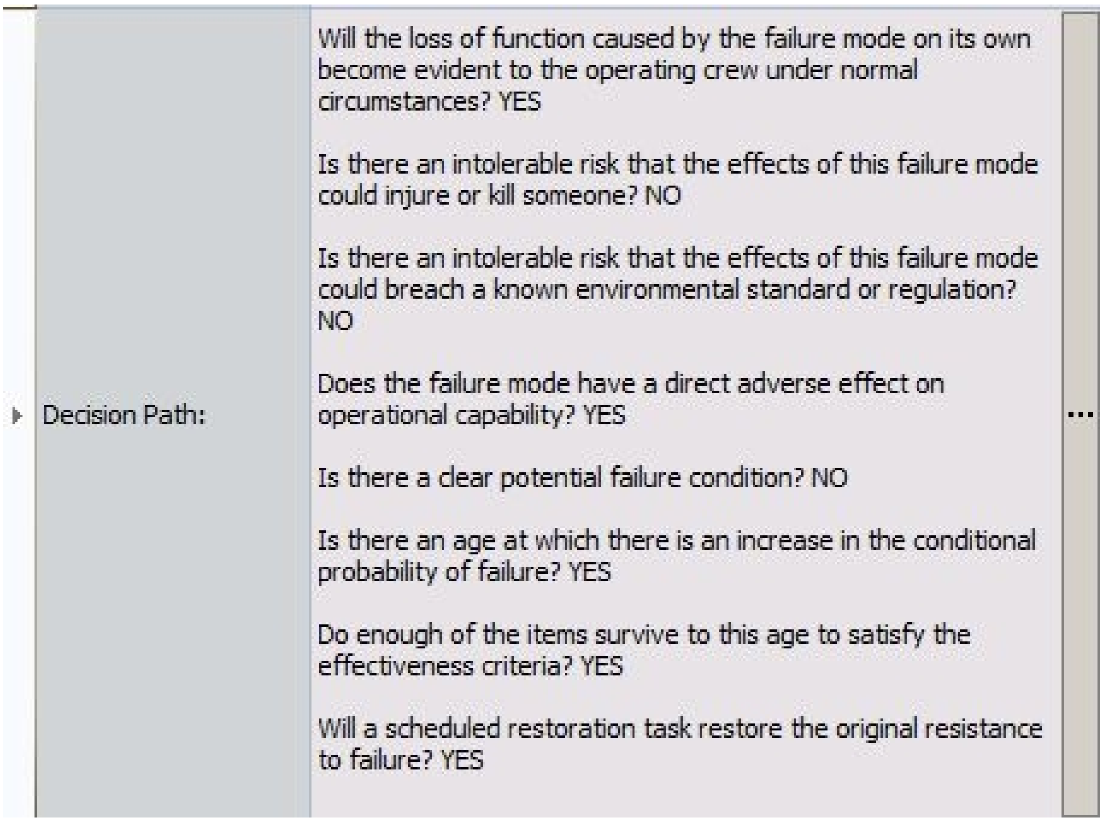



Figure 4.1: Fuel System HP Pump Seized - Decision Path

- ∗ Production effects: The locomotive must be shunted into the workshop from the operational yard.
- ∗ Failure repair: The locomotive will need to come to the workshop for unscheduled maintenance. It takes one fitter 3 hours to replace a failed fuel pump (from maintenance records).

### 4.2.4 Failure consequences: RCM decision logic and risk assessment

The author utilised the decision path tool built into RTRS; the tool is based on the decision diagram in figure 2.4. Figure 4.1 contains the decision logic for the failure mode example of a seized HP pump, as discussed in section 4.2.3.

Following the structure in figure 2.4, the first question on the decision path shown in figure 4.1 determines whether the function is hidden. The next two questions determine if the consequences are related to safety, the environment or are operational in nature. The following questions lead the user to evaluate the use of proactive maintenance tasks, including condition based maintenance, restoration and replacement. If none of these are technically feasible or worth doing, the final questions evaluate the default actions, which are comprised of: failure-finding tasks, run-to-failure, or redesign. This series of questions complies with Society of Automotive Engineers (2009) and figure 2.4.

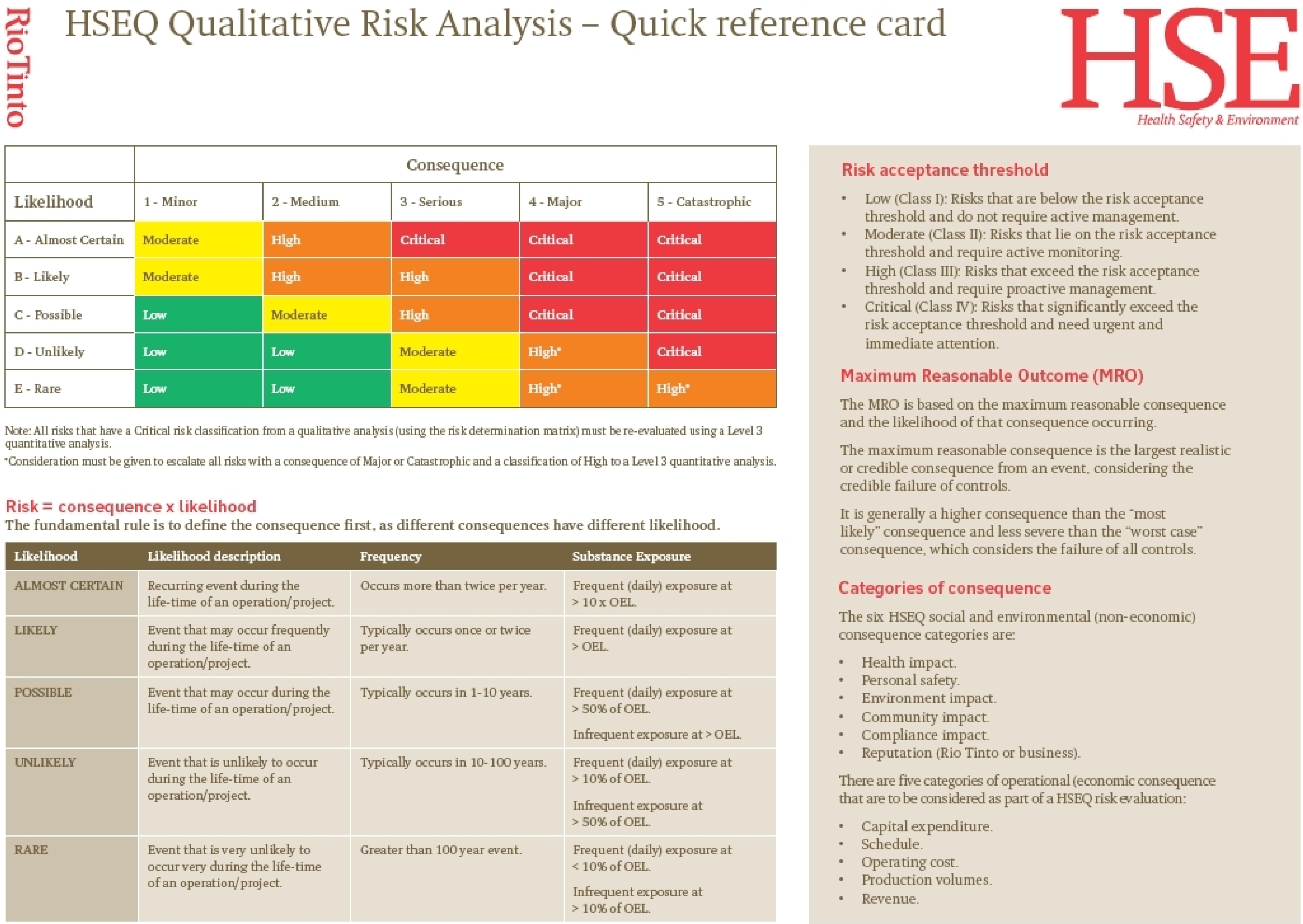
The risk assessment was carried out using the Rio Tinto risk matrix, shown in figures 4.2 and 4.3. Risk assessment is subjective by nature (Moubray 2001, pg. 101), but the Rio Tinto risk matrix aids the analyst to be more objective by providing criteria against which to assess the likelihood and severity of events. Note that the matrix is in the same format as figure 2.6, which is extracted from AS60300.

The risk data was entered into the forms displayed in figures I.7 and I.8. The key points to be noted are:

- Risk likelihood is evaluated against the service life of one locomotive, not the fleet of locomotives. For example, if a failure is likely to occur in one locomotive in the order of 10-20 years, then it may occur every year over the whole the fleet. The service life of one locomotive is selected as the appropriate basis for the risk likelihood assessment.
- Risk severity is assessed against the capital cost of replacement for the asset or the appropriate HSE standards.
- Economic effects are counted as \$50 per minute of train delay (established in section 3.6), and each minute of train delay causes one minute delay to the train behind it. Thus, a four hour delay caused by a locomotive failure will cause $\$50/minute \times 240 minutes \times 2 = \$24,000$ revenue loss.

In the case of a seized HP pump, the unmitigated risk is evaluated as high, based on the following assessment:

- The likelihood is assessed as likely; if no maintenance is done, it is likely that after a period of 8 years the locomotive would experience unreliable HP pumps and may fail one or more of the 12 pumps each year.
- The severity is assessed as moderate; the locomotive will require removal from service, increasing the cost of failure. Secondary damage to camshafts and power assemblies may also occur.



RioTinto

# HSEQ Qualitative Risk Analysis – Quick reference card

HSE
Health Safety & Environment

| | Consequence | | | | |
|---|---|---|---|---|---|
| **Likelihood** | 1 - Minor | 2 - Medium | 3 - Serious | 4 - Major | 5 - Catastrophic |
| A - Almost Certain | Moderate | High | Critical | Critical | Critical |
| B - Likely | Moderate | High | High | Critical | Critical |
| C - Possible | Low | Moderate | High | Critical | Critical |
| D - Unlikely | Low | Low | Moderate | High* | Critical |
| E - Rare | Low | Low | Moderate | High* | High* |

Note: All risks that have a Critical risk classification from a qualitative analysis (using the risk determination matrix) must be re-evaluated using a Level 3 quantitative analysis.
*Consideration must be given to escalate all risks with a consequence of Major or Catastrophic and a classification of High to a Level 3 quantitative analysis.

## Risk = consequence x likelihood

The fundamental rule is to define the consequence first, as different consequences have different likelihood.

| Likelihood | Likelihood description | Frequency | Substance Exposure |
|---|---|---|---|
| ALMOST CERTAIN | Recurring event during the life-time of an operation/ project. | Occurs more than twice per year. | Frequent (daily) exposure at > 10 x OEL. |
| LIKELY | Event that may occur frequently during the life-time of an operation/project. | Typically occurs once or twice per year. | Frequent (daily) exposure at > OEL. |
| POSSIBLE | Event that may occur during the life-time of an operation/ project. | Typically occurs in 1-10 years. | Frequent (daily) exposure at > 50% of OEL.<br>Infrequent exposure at > OEL. |
| UNLIKELY | Event that is unlikely to occur during the life-time of an operation/project. | Typically occurs in 10-100 years. | Frequent (daily) exposure at > 10% of OEL.<br>Infrequent exposure at > 50% of OEL. |
| RARE | Event that is very unlikely to occur very during the life-time of an operation/ project. | Greater than 100 year event. | Frequent (daily) exposure at < 10% of OEL.<br>Infrequent exposure at > 10% of OEL. |

## Risk acceptance threshold

- Low (Class I): Risks that are below the risk acceptance threshold and do not require active management.
- Moderate (Class II): Risks that lie on the risk acceptance threshold and require active monitoring.
- High (Class III): Risks that exceed the risk acceptance threshold and require proactive management.
- Critical (Class IV): Risks that significantly exceed the risk acceptance threshold and need urgent and immediate attention.

## Maximum Reasonable Outcome (MRO)

The MRO is based on the maximum reasonable consequence and the likelihood of that consequence occurring.

The maximum reasonable consequence is the largest realistic or credible consequence from an event, considering the credible failure of controls.

It is generally a higher consequence than the "most likely" consequence and less severe than the "worst case" consequence, which considers the failure of all controls.

## Categories of consequence

The six HSEQ social and environmental (non-economic) consequence categories are:

- Health impact.
- Personal safety.
- Environment impact.
- Community impact.
- Compliance impact.
- Reputation (Rio Tinto or business).

There are five categories of operational (economic consequence that are to be considered as part of a HSEQ risk evaluation:

- Capital expenditure.
- Schedule.
- Operating cost.
- Production volumes.
- Revenue.

Figure 4.2: Rio Tinto risk matrix, page 1

## Consequence descriptors

| Consequence | MINOR | MEDIUM | SERIOUS | MAJOR | CATASTROPHIC |
|---|---|---|---|---|---|
| Non-Economic (Social and Environmental) | | | | | |
| HEALTH | Reversible health effects of little concern, requiring first aid treatment at most.<br>Can include minor irritations of eyes, throat, nose and or skin, or minor unaccustomed muscular discomfort. | Reversible health effects of concern that would typically result in medical treatment.<br>Can include temperature effects; travel effects; stress; and sunburn. | Severe, reversible health effects of concern that would typically result in a lost time illness.<br>Can include acute/short-term effects associated with extreme temperature effects, or musculoskeletal effects, vibration effects, nervous system effects, some infectious diseases; and non falciparum malaria. | Single fatality or irreversible health effects or disabling illness.<br>Can include effects of suspected carcinogens, mutagens, teratogens and reproductive toxicants, progressive chronic conditions and/or acute/short-term high-risk effects. | Multiple fatalities or serious disabling illness to multiple people.<br>Can include effects of known human carcinogens, mutagens, teratogens and reproductive toxicants, and life-threatening respiratory sensitization and falciparum malaria. |
| SAFETY | Low level short term subjective inconvenience or symptoms.<br>Typically a first aid and no medical treatment. | Reversible injuries requiring treatment, but does not lead to restricted duties.<br>Typically a medical treatment. | Reversible injury or moderate irreversible damage or impairment to one or more persons.<br>Typically a lost time injury. | Single fatality and/or severe irreversible damage or severe impairment to one or more persons. | Multiple fatalities or permanent damage to multiple people. |
| ENVIRONMENT (on site) | Near-source confined and promptly reversible impact (typically a shift). | Near-source confined and short-term reversible impact (typically a week). | Near-source confined and medium-term recovery impact (typically a month). | Impact that is unconfined and requiring long-term recovery, leaving residual damage (typically years). | Impact that is widespread-unconfined and requiring long-term recovery, leaving major residual damage (typically years). |
| ENVIRONMENT (off site) | Not applicable. | Near-source confined and promptly reversible impact (typically a shift). | Near-source confined and short-term reversible impact (typically a week). | Near-source confined and medium-term recovery impact (typically a month). | Impact that is unconfined and requiring long-term recovery, leaving residual damage (typically years). |

| | | | | | |
|---|---|---|---|---|---|
| Economic (operational) (based on annualised figures for operating, production and revenue) | | | | | |
| Capital expenditure | < 1.6% | 1.6% - 5% | 5% - 10% | 10% - 30% | > 30% |
| Schedule | < 2.5% | 2.5% - 7.5% | 7.5% - 15% | 15% - 45% | > 45% |
| Operating costs | < 0.6% | 0.6% - 2.5% | 2.5% - 7.5% | 7.5% - 15% | > 15% |
| Production volumes | < 0.6% | 0.6% - 2.5% | 2.5% - 7.5% | 7.5% - 15% | > 15% |
| Revenue | < 0.25% | 0.25% - 1% | 1% - 3.5% | 3.5% - 7% | >7% |

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| Consequence | MINOR | MEDIUM | SERIOUS | MAJOR | CATASTROPHIC |
|---|---|---|---|---|---|
| COMMUNITY (community trust) | Tangible expressions of trust/mistrust amongst a handful of community members with no influence on public opinion and decision-makers. | Tangible expressions of trust /mistrust amongst a few community members with some influence on public opinion and decision-makers. | Tangible expressions of trust /mistrust amongst some community members with moderate influence on public opinion and decision-makers. | Tangible expressions of trust/mistrust amongst most community members with significant influence on decision-makers. | Widespread loss/gain of trust across the community setting the agenda for decision-makers and key stakeholders. |
| COMMUNITY (stakeholders) | Key civil/political stakeholder(s) express support/dissatisfaction informally. | Key civil/political stakeholder(s) express support/dissatisfaction informally. | Key civil/political stakeholder(s) threaten to oppose or disengage/strengthen offers to support or engage. | Key civil/political stakeholder(s) actively oppose or actively refuse to engage/actively support and engage. | Key civil/political stakeholder(s) actively oppose and actively get others to oppose/engaged and actively get others to support. |
| COMMUNITY (cultural heritage) | Repairable damage to site or item of low cultural significance. | Irreparable damage to site or item of low cultural significance. | Repairable damage to site or item of cultural significance. | Irreparable damage to site or item of cultural significance. | Irreparable damage to site or item of international cultural significance. |
| REPUTATION | Community complaint resolved via existing site procedures.<br>Impact on reputation of several work areas within an operation.<br>One off public exposure in local media, word of mouth or local mythologies. | Impact on reputation of Business Unit.<br>Significant public exposure in local media. | Impact on reputation of Product Group.<br>Comment from national NGO which impacts credibility with neighbours/regional government.<br>Public exposure in national media. | Impact on reputation of Rio Tinto Group.<br>Comment from international NGO.<br>Public exposure in international media. | Severe impact on reputation of Rio Tinto Group.<br>Severe prolonged comment from international NGO.<br>Greater than three years public exposure in international media. |
| CONFORMANCE /COMPLIANCE | Non-conformance with internal requirement with very low potential for impact.<br>Non-compliance with external/community commitment goes unnoticed by external party/parties, requiring minimal effort to correct. | Non-compliance with external or non-conformance with internal requirement with low potential for impact.<br>Non-compliance with community commitment, requiring limited effort to correct. | Non-compliance with external or non conformance with internal requirement with moderate potential for impact.<br>Moderate penalties for breach of legislation, contract, permit or licence.<br>Non-compliance with community commitment reported formally, requiring significant effort to correct. | Breach of licences, legislation, regulation or repeated non-compliance with high potential for prosecution.<br>Breach of contract with significant penalty clauses imposed.<br>Systemic non-conformance with Rio Tinto work cycles or standards with high potential for impact.<br>Breach of community commitment with high potential to cause business interruption, requiring significant effort to correct. | Suspended or severely reduced operations imposed by regulators.<br>Breach of community commitment results in direct loss of established consents with widespread secondary effects. |

Figure 4.3: Rio Tinto risk matrix, page 2

### 4.2.5 Recommendations and mitigated risk assessment

The maintenance task recommendation and mitigated risk assessment is conducted together, and recorded in the forms shown in figures I.9, I.10, I.11 and I.12. In the case of the seized HP pump, a recommendation for scheduled replacement is made and the mitigated risk is assessed as 5 (low).

The recommendation includes the following information:

**Task interval.** The high pressure fuel pump scheduled replacement has been tentatively recommended at 17,000MWHrs (half engine life); however, there is further work required to justify the service life as it is currently 11,000MWHrs (one third of engine life) against the manufacturer's recommendation of 13,000MWHrs.

**Recommended resource.** The type of labour, materials or services required to complete the task; in this case, a the labour required is a diesel mechanic and the materials are refurbished pumps.

**Estimated costs.** The cost of labour, materials and services.

## 4.3 Chapter Summary

Chapter 4 has presented an overview of the process undertaken to determine engine subsystem functions, functional failures, failure modes, failure effects, failure consequences and recommended actions, or default actions, to limit risk to an acceptable level.

# Chapter 5

# Reliability-Centered Maintenance Analysis Results

## 5.1 Chapter Overview

This chapter presents a summary of the analysis results. In order to present the information, it is divided into three sections; the functional analysis, FMEA and failure consequences and the recommended maintenance tactics, including a comparison with the current maintenance tactics. To review the complete analysis, please refer to the accompanying spreadsheet mayne_caleb_goh_rcm_data.xls.

## 5.2 Functions and Functional Failure Analysis

The identified functions, performance paramters, function type and their respective functional failures are included in figures 5.1 and 5.2.

| Function Name | Function Performance Parameters | Function Type | Functional Failure Name |
|---|---|---|---|
| 01. Fuel System: LP circuit to provide clean, pressurised fuel at design temperature to the twelve high pressure fuel pumps. | Flow rate: 48L/min<br>Operating Pressure: 420kPa (Notch 8) to 640kPa<br>Relief Pressure: 1,020kPa<br>Temperature: 19 to 55 degrees C<br>Cleanliness: Filters remove particles greater than 5 micron, no ISO figure specified. H. Carlisle advises it is likely to be in th | Primary | 1. No fuel is provided to the HP fuel pumps |
| | | | 2. Fuel pressure is lower than 420kPa |
| | | | 3. Fuel flow is less than 48L/min. |
| | | | 4. Fuel pressure above 896kPa. |
| | | | 5. Fuel contains dirt particles greater than 5 microns in size. |
| | | | 6. Fuel is cooler than 19 degrees celsius |
| | | | 7. Fuel is warmer than 55 degrees celsius |
| | | | 8. Fuel contains water |
| 02. Fuel System: HP fuel pumps to provide pressurised, timed, metered fuel to the injectors. | Pressure: Max injection pressure 26000psi/1800bar<br>Injection Timing: 5 degrees BTDC (Notch 8)<br>Fuel Value: 2150cu/mm sq<br>Fuel Limit: Adaptive FL2600 | Primary | 1. Complete HP fuel pump failure - supplies no fuel |
| | | | 2.Partial failure of HP fuel pump, delivers fuel but does not time or meter fuel appropriately or supplies fuel below required pressure |
| 03. Fuel System: HP fuel injectors to supply the metered fuel to the cylinder in the designed spray pattern, in an atomised state. | Injector needle to lift at 6500psi/450bar | Primary | 1. Complete Injector failure - supplies no fuel |
| | | | 2. Supplies fuel in the wrong spray pattern or not atomised |
| | | | 3. Injector leaks excess fuel into the cylinder |
| 04. Fuel System: Contain all fuel. | (blank) | Secondary | 1. Fails to contain fuel |
| 05. Fuel System: Return HP fuel to cool and lubricate HP components and drain back to the fuel tank. | (blank) | Secondary | 1. Return HP fuel does not lubricate the HP components |

Figure 5.1: RCM Functional Analysis, part 1

| Function Name | Function Performance Parame | Function Type | Functional Failure Name |
|---|---|---|---|
| 06. Long Power Assembly: Transmit energy to and from the working gas | 4 Stroke Diesel Engine<br>12 power assemblies producing 4500 HP total - 375 HP per power assembly.<br>Compression Ratio: 16.5:1<br>Bore and Stroke: 250x320mm<br>Maximum RPM: 1050 | (blank) | 01. Fails to transmit energy to and from the working gas |
| 07. Long Power Assembly: Facilitate gas exchange | (blank) | (blank) | 01. Charge air and exhaust gasses cannot be exchanged |
| 08. Long Power Assembly: Transfer energy to and from the rotating crankshaft | 4 Stroke Diesel Engine<br>12 power assemblies producing 4500 HP total - 375 HP per power assembly.<br>Compression Ratio: 16.5:1<br>Bore and Stroke: 250x320mm<br>Maximum RPM: 1050 | Primary | 01. Fails to transfer linear energy<br>02. Fails to rotate |
| 09. Long Power Assembly: Contain pressurised gasses | 4 Stroke Diesel Engine<br>12 power assemblies producing 4500 HP total - 375 HP per power assembly.<br>Compression Ratio: 16.5:1<br>Bore and Stroke: 250x320mm<br>Maximum RPM: 1050 | Secondary | 01. Combustion gasses leak to crankcase<br>02. Combustion gasses leak to inlet or exhaust manifolds<br>03. Combustion gasses leak to atmosphere |
| 10. Long Power Assembly: Contain fluids - coolant and oil | Coolant: Nalco 2100 | Primary | 01. Fails to contain engine coolant or oil. |
| 11. Combustion Air System: Provide sufficient flowrate of air at 172kPa (25psi) and 38 degrees C. | Function is given at Notch 8 parameters. | Primary | 01. Fails to develop sufficient flow and pressure<br>02. Fails to maintain sufficient air flow and pressure<br>03. Air temperature above 38 degrees Celsius |
| 12. Combustion Air System: Provide clean air free of dirt particles. | (blank) | Primary | 01. Combustion air contains dust or other foreign particles |
| 13. Combustion Air System: Contain fluids - coolant and oil | (blank) | Secondary | 01. Fails to contain oil or coolant |

Figure 5.2: RCM Functional Analysis, part 2

Table 5.1: Summary of recommended maintenance task changes

| Change Significance | Count |
|---|---|
| No Change | 71 |
| Minor | 11 |
| Moderate | 7 |
| Major | 0 |
| **Total:** | **89** |

## 5.3 Failure Modes, Failure Effects and Failure Consequences analysis

120 failure modes have been identified through the analysis; it is not practical to present them all in this section. As such, notable extracts have been included in figures 5.3 to 5.9. The entire list of FMEA short descriptions has been included in appendix J. For the complete analysis, please refer to the Excel document that accompanies this dissertation, mayne_caleb_goh_rcm_data.xls.

## 5.4 Recommendations Summary, Mitigated Risk Assessments and Current Tactics

The complete recommendations summary and current tactics comparison is included in appendix K. An extract of notable recommendations is included in figures 5.10 and 5.11, which will be explored in the discussion. The recommendation changes are classified into minor, moderate or major changes; a summary of this classification is presented in table 5.1, which shows that the majority of tasks require no change, indicating that the regime is generall optimised with some improvements identified.

One of the research objectives is to identify failure modes that are not addressed by a maintenance task. Very few of these were identified; they are included in figure 5.12.

Each task type and the corresponding code is listed in table 5.2, while the risk level classifications are provided in table 5.3. The reader can also refer to figure I.7 to view the risk matrix.

Table 5.2: Maintenance task classification

| Code | Task Classification |
|---|---|
| SCH | Scheduled preventive maintenance |
| CBM | Condition Based Maintenance |
| DSN | Redesign opportunity |
| PROC | Work instruction or procedure change |
| TRN | Staff training |
| NSM | No scheduled maintenance - run to fail |

Table 5.3: Maintenance task classification

| Value Range | Risk Classification |
|---|---|
| 0-1 | Low |
| 1-5 | Medium |
| 5-125 | High |
| 125-5000 | Very High |

| Failure Mode Identification | Failure Mode Long Description | Failure Pattern | Effect Name | Failure Effect Long Description | Driving Risk Category | Unmitigated Risk | Basis for Risk Assessment |
|---|---|---|---|---|---|---|---|
| 01.07.02. Hot return fuel from engine entering fuel tank directly next to fuel intake. | Known issue with an OEM redesign in process. Due to hot return fuel from engine entering fuel tank directly next to fuel intake. | Rapid Wearout | Fuel transfer pump fails; Locomotive shuts down | Evidence of Failure:<br>Fuel transfer pump motor/inverter fails due to long term overheating. Fuel pump circuit breaker trips. Locomotive becomes a dead unit.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>Depending on the location, Rail Operations may be able to run the unit offline back to the port but may also require rescue locomotives. This is very disruptive to the rail network.<br>Requires locomotive to return to workshop.<br><br>Secondary Damage:<br>Nil.<br><br>Failure Repair:<br>Takes 1 maintainer 2 hours to replace pump. | Operating cost | 2.51 | Likelihood:<br>MTBF of fuel pumps is approximately 4.5 years, giving a 'probable' likelihood.<br>Severity:<br>MRO: this fault can cause a 4 hour delay if it occurs in a critical network location. At $50/minute, and 1 minute knock on for each primary minute, this is $24,000. |
| 02.01.01. HP pump seizes | HP Pump seizes due to a combination of any or all of the following over an extended period of time: wear, cavitation, corrosion.<br><br>This leads to: fatigue cracking, material liberation.<br><br>Causing: Galling/scuffing/cracking which causes the pump to seize.<br><br>Modelling indicates HP pumps have a wear out failure mode, refer to reliability distribution: Locomotive.EVO.Fuel HP Fuel Pump.Rev 2 | Wearout | HP Pump ceases to function, complete failure of cylinder but locomotive still makes horsepower. | Evidence of Failure:<br>May result in locomotive derating, but in most cases the locomotive will overload other power assemblies. The failure may be detected by hearing the cylinder missing but this should not be relied upon. The failure will be detected if more power assemblies fail to produce power and the locomotive cannot make full horsepower.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>Nil.<br><br>Secondary Damage:<br>Most likely case is that the pump seizes at the top of its stroke and no further damage is caused.<br>Worst possible case, the pump may seize at the bottom of its stroke and push the pump off its mount, snapping the bolts, cracking the high pressure line & wrecking the power assembly, requiring power assembly replacement.<br><br>Failure Repair:<br>The locomotive will need to come to the workshop for unscheduled maintenance. Takes one fitter 3 hours to replace a failed fuel pump (SAP record). | Operating cost | 10 | Likelihood:<br>If no maintenance is done, it is likely that after a period of time (5-8 years) the locomotive would experience unreliable HP pumps and may fail one or more of the 12 pumps each year.<br>Severity:<br>Each pump is 2500, with an unplanned cost estimated at double = $5000. Not expected to cause significant delays.<br>If left to run with no intervention/detection, failed fuel pumps can cause significant damage to camshafts, fuel pump mounts, can introduce metal debris into the lubricating oil. Unlikely to damage power assembly on an Evo. |
| 02.01.02. Solenoid fails to operate | There is one SAP record indicating this failure mode; not enough to model using the Weibull distribution. Random failure pattern assumed at this point.<br>The solenoid doesn't appear to be in the BOM so is not a currently a maintainable item. | Constant/random | Power assembly will no longer produce power but locomotive will still make full horsepower. | Evidence of Failure:<br>The locomotive will compensate by producing more power from the other power assemblies. The failure will not be detected unless more power assemblies stop producing power and the locomotive cannot make full horsepower.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>Nil.<br><br>Secondary Damage:<br>Engine efficiency will be decreased due to over loading of the other power assemblies but no further damage will be caused.<br><br>Failure Repair:<br>To repair the failure, the HP pump must be replaced as the solenoid is not a replaceable unit. | Operating cost | 0.05 | Likelihood:<br>Only one recorded failure; not enough to model. Assume random/constant failure pattern. Given that there has been only one recorded instance, it is very unlikely to occur on any one locomotive.<br>Severity:<br>Will not cause secondary damage and should not cause a delay, so minimal damage.<br>Unplanned replacement estimated to cost double that of planned replacement. |

Figure 5.3: FMEA and Failure Consequences extract, part 1

| Failure Mode Identification | Failure Mode Long Description | Failure Pattern | Effect Name | Failure Effect Long Description | Driving Risk Category | Unmitigated Risk | Basis for Risk Assessment |
|---|---|---|---|---|---|---|---|
| 02.01.03. Fuel pump roller guide pin loosened | The guide pin (located in the power assembly strongback) that holds the roller and pushrod in line with the camshaft was not loctited properly allowing the bolt to loosen and fall out. This allows the roller and pushrod to rotate.<br>This failure mode was a manufacture defect and has not been seen again in the Evo fleet. No need for a maintenance recommendation is necessary at this point in time. | Infant Mortality | HP pump ceases to function and is severely damaged along with the camshaft | Also causes the power assembly to fail. Introduces metal filings into the lubricating oil sump.<br>Failure does not occur any more; no need to evaluate any further. | | | |
| 02.01.04. Fuel Pump Roller Cracked | | Wearout | HP pump ceases to function and is severely damaged along with the camshaft and power assembly strongback | Evidence of Failure:<br>This failure may be detected by listening to the engine as the pump will be very noisy, but is not to be relied upon.<br><br>Rolling contact fatigue causes subsurface fatigue cracking. Prior to cracking failure, the roller will display significant fatigue spalling.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>The only production effect is the requirement to bring the locomotive in to the workshop for unscheduled maintenance.<br><br>Secondary Damage:<br>Causes secondary damage to the cam section, requiring replacement of both the cam section and fuel pump.<br><br>Failure Repair:<br>This will take 1 fitter 5 hours to repair. | Operating cost | 2.51 | Likelihood:<br>Not enough data to model failure mode pattern. Suspect wearout/aging failure pattern, as it is due to fatigue failure. Do not know what the PF interval is, but expect it to be greater than 4 months (current servicing interval).<br>Severity:<br>Causes secondary damage to camshaft. Unlikely to damage pump. Ref SAP 22037346,23486514. Not identical failure mode but similar in that the fuel pump and cam section are damaged. (guide pin loosened).<br>Note that 22126790 appears to be due to the guide pin issue and has required replacement of whole power assembly. Need to confirm if this can be the case that cracked roller can damage entire power assembly, and how. |
| 02.01.05. Pump roller return spring breaks due to fatigue | | Wearout | Secondary damage caused to engine | This failure mode has not been seen at RTIO on the evolution fleet but is a well known failure mode in the Dash 9 fleet.<br><br>Evidence of Failure:<br>Driver may detect the fault by hearing the power assembly missing or noise due to the roller bouncing on the camshaft, but this cannot be relied upon.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>The only production effect will be the requirement to bring the locomotive to the workshop for unscheduled maintenance.<br><br>Secondary Damage:<br>Pump roller 'bounces' on camshaft causing damage to the roller and cam.<br>Debris will be introduced to the lubricating oil & internal engine components.<br>Damage to cam section.<br><br>Failure Repair:<br>It will take one fitter 5 hours to change the fuel pump and cam section. | Operating cost | 2.51 | Likelihood:<br>No failures of this mode have been observed, but this may be due to the current maintenance strategy mitigating the failure mode so the probability was left at probable.<br>Severity:<br>Should not cause a delay. Likely to require replacement of cam section (due to bouncing) and pump. SAP records indicate this would cost approx $5-10k.<br>SAP:<br>22037346<br>21953691<br>23486514<br>22385034<br>22126790 |

Figure 5.4: FMEA and Failure Consequences extract, part 2

| Failure Mode Identification | Failure Mode Long Description | Failure Pattern | Effect Name | Failure Effect Long Description | Driving Risk Category | Unmitigated Risk | Basis for Risk Assessment |
|---|---|---|---|---|---|---|---|
| 02.02.01. HP Fuel pump internal seals worn | Component tolerances worn allowing fuel to leak.<br>Modelling indicates HP pumps have a wear out failure mode, refer to reliability distribution: Locomotive.EVO.Fuel HP Fuel Pump.Rev 2 | Wearout | Individual cylinder efficiency drops; other cylinders make extra power | Evidence of Failure:<br>If enough pumps are worn, the locomotive will start to derate.<br><br>HSE Effects:<br>Nil.<br>Operational and Production Effects:<br>Failure requires the locomotive to be brought to the workshop for HP fuel pump replacement<br><br>Secondary Damage:<br>Locomotive fuel efficiency will be decreased.<br>Excess fuel leakage returns to tank via the HP drain line.<br>No secondary damage is caused.<br><br>Failure Repair:<br>Best detected by WCD. DCD or pop test will detect if the wear is severe, but the pop test does not require a lot of fuel so it may still pass.<br>Takes one fitter two hours to replace HP fuel pump. | Operating cost | 0.251 | Likelihood:<br>If no maintenance were performed, this failure mode is likely to occur.<br>Severity:<br>Will not cause a delay. Loco may derate.Can be planned in as a PM02 and not cause excessive unplanned maintenance costs. |
| 03.02.01. Injector atomising nozzles worn | Nozzle holes are enlarged and/or edge is not sharp due to wear. | Wearout | Spray pattern quality is reduced, decreasing fuel efficiency and power | Evidence of Failure:<br>The engine will start to blow more black smoke than usual.<br><br>HSE Effects:<br>Nil<br><br>Operational and Production Effects:<br>The only operational effect is requiring the locomotive to be brought to the workshop for unscheduled maintenance.<br><br>Secondary Damage:<br>No physical damage is caused by the failure. Long term, piston and cylinder damage may occur causing power assembly failure.<br><br>Failure Repair:<br>injector replacement requires the locomotive to be brought to the workshop heavy maintenance road. Takes one fitter 2 hours to replace injector. | Operating cost | 2.51 | Likelihood:<br>If no maintenance is performed, it is likely that the failure mode will occur on each loco.<br>Severity:<br>No real ill effects; only if the loco was left to run like that for an extended period but it is likely to be detected by the engine blowing lots of black smoke. This will cause unplanned maintenance. |
| 03.02.02. Injector nozzle blocked or partially blocked due to carbon build up. | This failure mode is considered to be caused by other issues rather than the injector itelf. No further analysis to be conducted.<br>caused by:<br>excessive idling<br>poor quality fuel<br><br>also is a secondary effect of other injector or pump failure (too much fuel) but this is not considered here.<br><br>This failure mode has not been seen at RTIO in the Evolution fleet. | Constant/random | Cylinder does not perform efficiently | Evidence of Failure:<br>Smoking exhaust stack. If there are enough cylinders affected, the loco may not be able to make power.<br>HSE Effects:<br>Nil.<br>Operational and Production Effects:<br>If it is severe enough, the loco will derate but unlikely to cause a delay.<br>Secondary Damage:<br>Nil.<br>Failure Repair:<br>Requires the loco to return to heavy maintenance for injector replacement. Requires 1 fitter for 2 hours for one injector. | Operating cost | 0.1 | Likelihood:<br>Not witnessed at RTIO; considered unlikely in our operation.<br>Severity:<br>Doesn't have severe consequences. |

Figure 5.5: FMEA and Failure Consequences extract, part 3

| Failure Mode Identification | Failure Mode Long Description | Failure Pattern | Effect Name | Failure Effect Long Description | Driving Risk Category | Unmitigated Risk | Basis for Risk Assessment |
|---|---|---|---|---|---|---|---|
| 03.03.01. Injector needle lift pressure low due to broken or softened spring | | Wearout | Cylinder does not perform efficiently, engine blows black smoke. | Evidence of Failure:<br>Excess fuel will be injected into the cylinder and the fuel will not be atomised because the full pressure is not able to be developed. Depending on the severity, the engine may blow excess black smoke and carbon out the exhaust or excess fuel may be blown out the exhaust and show up as white smoke or flames.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>Nil.<br><br>Secondary Damage:<br>in extreme cases,<br>Piston scuffing/seizure (due to liner being washed by diesel particles), piston crown damage (due to diesel droplets combusting directly on the piston), oil dilution (unburnt diesel droplets entering the sump), eventually causing power assembly failure. This will be detected by the Crankcase Over Pressure Sensor and the engine will then be shut down. This failure mode may also cause greater injector damage, including 'uncapping' which will cause a power assembly failure.<br><br>Can also cause valve damage due to lean combustion overheating exhaust gasses.<br><br>Failure Repair:<br>injector replacement requires the locomotive to be brought to the workshop heavy maintenance road. Takes one fitter 2 hours to replace injector. If trouble shooting is required it will take longer. | Operating cost | 25.1 | Likelihood:<br>This failure mode has been witnessed in recent injector teardown testing.<br>If no maintenance is performed this failure mode is likely to occur after a period of 3-4 years.<br>Severity:<br>Can cause washed bores, causing piston/liner scoring and failed power assemblies. Cost is approximately $30,000, reference sap order32997589.<br>MRO: this fault can cause a 4 hour delay if it occurs in a critical network location. At $50/minute, and 1 minute knock on for each primary minute, this is $24,000. |
| 03.03.02. Injector needle seizes due to excessive wear | Wear caused by:<br>Cavitation erosion,<br>Normal wear on overextended life, leading to fatigue cracking/galling/scuffing/seizure. | Wearout | Injector doesn't seal; leaks fuel into cylinder before and after intended fuel injection window | Evidence of Failure:<br>Detected by erratic locomotive behaviour. May result in locomotive derating. Depending on severity, the engine may blow black smoke or excess fuel may be blown out the exhaust and show up as white smoke or flames. SAP orders indicate black smoke in certain notches.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>Nil.<br><br>Secondary Damage:<br>Possible secondary damage in extreme cases:<br>Piston scuffing/seizure (due to liner being washed by diesel particles), piston damage due to fuel burning on the piston surface, oil dilution (unburnt diesel droplets entering the oil pan), most likely that when the piston/power assembly fails, it will cause a crank case overpressure and the engine will then shutdown.<br><br>Failure Repair:<br>injector replacement requires the locomotive to be brought to the workshop heavy maintenance road. Takes one fitter 2 hours to replace injector. If trouble shooting is required it will take longer. | Operating cost | 25.1 | Likelihood:<br>If no maintenance is performed this failure mode is likely to occur after a period of 3-4 years.<br>Severity:<br>Can cause washed bores, causing piston/liner scoring and failed power assemblies. Cost is approximately $30,000, reference sap order32997589.<br>MRO: this fault can cause a 4 hour delay if it occurs in a critical network location. At $50/minute, and 1 minute knock on for each primary minute, this is $24,000. |
| 03.03.03. Injector needle, seat, pressure pin worn. | Due to normal wear and tear over service life. Not because of contaminated diesel. | Wearout | Cylinder does not perform efficiently, engine blows black smoke. | Evidence of Failure:<br>Depending on the severity, the engine may blow black smoke or excess fuel may be blown out the exhaust and show up as white smoke or flames.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>If the locomotive is shut down in a critical network location, rescue locomotives will be required causing significant delays that may be 4 hours long.<br><br>Secondary Damage:<br>Secondary maintenance impacts:<br>wear on the pressure pin (or softened injector spring) can decrease needle lift pressure, increasing needle lift height and causes high impact reseating, severe cases causing nozzle to crack (injector 'uncapping'). Then due to streams of diesel being injected (no nozzle to atomise or valve seat to seal) Piston scuffing/seizure (due to liner being washed by diesel particles), piston damage due to fuel burning on the piston surface, oil dilution (unburnt diesel droplets entering the oil pan), most likely that when the piston/power assembly fails, it will cause a crank case overpressure and the engine will then shutdown.<br><br>Failure Repair:<br>injector replacement requires the locomotive to be brought to the workshop heavy maintenance road. Takes one fitter 2 hours to replace an injector. | Operating cost | 10 | Likelihood:<br>Failure mode not witnessed at RTIO but it is thought possible if no maintenance is performed this failure mode is likely to occur after a period of 3-4 years.<br>Severity:<br>Can cause washed bores, causing piston/liner scoring and failed power assemblies. Cost is approximately $30,000, reference sap order32997589.<br>MRO: this fault can cause a 4 hour delay if it occurs in a critical network location. At $50/minute, and 1 minute knock on for each primary minute, this is $24,000. |

Figure 5.6: FMEA and Failure Consequences extract, part 4

| Failure Mode Identification | Failure Mode Long Description | Failure Pattern | Effect Name | Failure Effect Long Description | Driving Risk Category | Unmitigated Risk | Basis for Risk Assessment |
|---|---|---|---|---|---|---|---|
| 03.03.04. Needle and seat degraded | due to normal wear and tear over service life. Needle/seat may be suffering wear, cavitation or corrosion.<br>not because of contaminated diesel. | Wearout | Cylinder does not perform efficiently, engine blows black smoke. | Evidence of Failure:<br>Engine will blow excess black smoke.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>If the loco shuts down due to COPS (as per secondary damage below) in a critical location, the train may require rescue locomotives, causing significant network disruption and delay.<br><br>Secondary Damage:<br>In the long run, the following effects may occur:<br>Piston crown damage (due to diesel droplets combusting directly on the piston), oil dilution (unburnt diesel droplets entering the sump), eventually causing power assembly failure. This will be detected by the Crankcase Over Pressure Sensor and the engine will then be shut down.<br><br>Failure Repair:<br>injector replacement requires the locomotive to be brought to the workshop heavy maintenance road. Takes one fitter 2 hours to replace injector. If trouble shooting is required it will take much longer. | Operating cost | 25.1 | Likelihood:<br>If no maintenance is performed this failure mode is likely to occur after a period of 3-4 years.<br>Severity:<br>Can cause piston damage, leading to a failed power assembliy. Cost is approximately $30,000 to replace, reference sap order32997589.<br>MRO: this fault can cause a 4 hour delay if it occurs in a critical network location. At $50/minute, and 1 minute knock on for each primary minute, this is $24,000. |
| 07.01.01. Pushrod snapped. Root cause unknown. | Modelling indicates a random failure pattern -<br>Locomotive.Evo.Power Assembly.Cracked Push Rods<br>8114 R3 inlet pushrod snapped the end off.<br>SAP notifications:<br>18443123<br>18423470<br>11520997<br>13699084<br>22730621 | Random | Low oil pressure alarm; locomotive shuts down | Evidence of Failure:<br>Pushrod failure renders the power assembly dead. Fuel is still injected and the cylinder 'soups up'. Fuel leaks past the piston rings into the sump, diluting the oil enough to cause low lubricating oil pressure.<br><br>HSE Effects:<br>Nil.<br>Operational and Production Effects:<br>Depending on the location, Rail Operations may be able to run the unit offline back to the port but may also require rescue locomotives, which is very disruptive to the rail network (delays can be 4hrs+).<br>Requires locomotive to return to workshop.<br><br>Secondary Damage:<br>Nil. Cylinder is not damaged because fuel lubricates the cylinder. Lubricating oil is ruined by fuel dilution.<br><br>Failure Repair:<br>Pushrod is replaced. Lube oil replaced. Takes 2 fitters 9 hours to diagnose and repair the fault. | Operating cost | 10 | Likelihood:<br>Severity:<br>MRO: this fault can cause a 4 hour delay if it occurs in a critical network location.<br>Costs:<br>ref sap order32997589<br>Cost of oil isn't captured here, add $5000 for oil. |
| 11.01.08. Baggy air filter clogged | | Wearout | Locomotive performance limited; logs an alarm | Evidence of Failure:<br>Loco will log alarm 01-0001 - Air filter differential pressure>14 inches of water at N7. A number of other alarms relating to derating or turbo surge will be logged.<br>Physically, the Loco will blow lots of black smoke due to over-fuelling and lack of air.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>Should not cause a delay because the locomotive will only be de-rated. Alarms will be logging well before significant limitation of power occurs.<br><br>Secondary Damage:<br>Running clogged air filters increases the amount of particles that pass through the filter. Over the long term, this causes damage to the turbo, valve train, pistons, cylinders and bottom end components.<br><br>Failure Repair:<br>Baggy air filters require replacement. Takes 1 fitter 0.5 hours to replace. | Operating cost | 100 | Likelihood:<br>If no maintenance is performed, it is considered highly likely that each locomotive will suffer from clogged baggy filters once a year.<br>Should not cause a delay because the locomotive is not a failure.<br>Severity:<br>If filters are run clogged, the performance can be degraded and dirt particles can pass through. This causes premature engine wear which is considered to be moderate in nature because the loco will log alarms that will alert the driver in the relatively early stages of clogging. |

Figure 5.7: FMEA and Failure Consequences extract, part 5

| Failure Mode Identification | Failure Mode Long Description | Failure Pattern | Effect Name | Failure Effect Long Description | Driving Risk Category | Unmitigated Risk | Basis for Risk Assessment |
|---|---|---|---|---|---|---|---|
| 11.02.01. Turbo discharge o-ring leaking boost air | | Increasing (zero early/random) | Boost air leak | Evidence of Failure:<br>Most of the time the failure will be minor in nature and not be detected unless someone is walking around inspecting the engine while it is loaded.<br>If the failure became very advanced after a long period of time, the operator is alerted by either the loco shedding amps or fault codes indicating turbo surging (01-0167 Engine RPM Raised To Avoid Turbo Surge).<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>Unlikely to cause a delay; if significant enough, requires the locomotive to be shunted from service for unscheduled shopping. However, most of the time it is scheduled to align with a 4 monthly service (Ref SAP 22350384,22630087,2294834).<br><br>Secondary Damage:<br>Nil.<br><br>Failure Repair:<br>O-ring requires replacement. Takes 1 fitter 1 hour to replace. Ref SAP 22830561, 22353143. | Operating cost | 0.251 | Likeilhood:<br>SAP records show 15 failures. The nature of the failure being minor means that a lot of failures have probably been masked by component changeouts of turbochargers and flexible air ducts. Judged to be a probable likelihood.<br>Severity:<br>Minor impacts - generally no operational delays, repair cost is minimal. Can usually be scheduled to align with a scheduled service. |
| 11.02.07. 8.5" Aluminium Air to Air Intercooler Inlet flange cracked due to fatigue | Fatigue crack.<br>8140-8156 are abnormally affected by this problem; it appears there is something different about this fleet. Modelling indicates a beta of 2, indicating reliability will get worse with age. | Wearout | Boost air leak | Evidence of Failure:<br>Most of the time the failure will be minor in nature and not be detected unless someone is walking around the engine while it is loaded.<br>If the failure became very advanced after a long period of time, the operator is alerted by either the loco shedding amps or fault codes indicating turbo surging (01-0167 Engine RPM Raised To Avoid Turbo Surge).<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>Unlikely to cause a delay; if significant enough, requires the locomotive to be shunted from service for unscheduled shopping. However, most of the time it is scheduled to align with a 4 monthly service (Ref SAP 22350384,22630087,2294834).<br><br>Secondary Damage:<br>Nil.<br><br>Failure Repair:<br>O-ring requires replacement. Takes 1 fitter 1 hour to replace. Ref SAP 22830561, 22353143. | Operating cost | 0.251 | Likeilhood:<br>SAP records show 15 failures. The nature of the failure being minor means that a lot of failures have probably been masked by component changeouts of turbochargers and flexible air ducts. Judged to be a probable likelihood.<br>Severity:<br>Minor impacts - generally no operational delays, repair cost is minimal. Can usually be scheduled to align with a scheduled service. |
| 11.02.06. Air based intercooler leaking boost air due to fatigue cracking or erosion. | Not enough data to model to determine failure pattern or characteristic life. Fatigue cracking and erosion not separated because they are both age related and not enough data exists to make a separate recommendation.<br>One failure recorded: SAP 31786264, loco 8126. Referred to the failure as 'collapsed intercooler'. | Wearout | Locomotive suffers from turbo surging | Evidence of Failure:<br>Operator is alerted by either the loco shedding amps or fault codes indicating turbo surging (01-0167 Engine RPM Raised To Avoid Turbo Surge).<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>Unlikely to cause a delay; requires the locomotive to be shunted from service for unscheduled shopping.<br><br>Secondary Damage:<br>Nil. If it were to continue unchecked, the turbo may be damaged but this is unlikely because the operator is unlikely to ignore the problem.<br><br>Failure Repair:<br>A2A flange requires replacement. Takes 2 fitters 4.5 hours (Ref SAP 33037273 and 23925557). | Operating cost | 0.251 | Likeilhood:<br>8140-8156 suffered this problem much worse than all other locos. 12 failures of this sort in this 17 locos. Considered probable for this fleet.<br>Severity:<br>Minor impacts - generally no operational delays, repair cost is minimal. But it does require an unscheduled shopping. |

Figure 5.8: FMEA and Failure Consequences extract, part 6

| Failure Mode Identification | Failure Mode Long Description | Failure Pattern | Effect Name | Failure Effect Long Description | Driving Risk Category | Unmitigated Risk | Basis for Risk Assessment |
|---|---|---|---|---|---|---|---|
| 11.03.01. Air based intercooler fan bearings seized | | | Loco Air inlet manifold temperature high; loco derates | Evidence of Failure:<br>Locomotive will log an alarm relating to hot preturbine temperature or turbo surging.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>Should not cause a delay - locomotive will only derate, not fail.<br><br>Secondary Damage:<br>Not considered likely to cause secondary damage.<br><br>Failure Repair:<br>Takes 1 electrician 3 hours to replace the fan. | Operating cost | 2.51 | Likelihood:<br>Considered probable if air to air fan is run for the entire life of the locomotive.<br>Severity:<br>Doesn't cause any secondary damage or operational delays, considered to be low consequence. |
| 11.03.02. Air based intercooler fan failed; insulation broken down causing a ground fault. | | Wearout | Loco Air inlet manifold temperature high; loco derates | Evidence of Failure:<br>Locomotive will log an alarm relating to hot preturbine temperature or turbo surging.<br><br>HSE Effects:<br>Nil.<br><br>Operational and Production Effects:<br>Should not cause a delay - locomotive will only derate, not fail.<br><br>Secondary Damage:<br>Not considered likely to cause secondary damage.<br><br>Failure Repair:<br>Takes 1 electrician 3 hours to replace the fan. | Operating cost | 2.51 | Likelihood:<br>Considered probable if air to air fan is run for the entire life of the locomotive.<br>Severity:<br>Doesn't cause any secondary damage or operational delays, considered to be low consequence. |

Figure 5.9: FMEA and Failure Consequences extract, part 7

| Recommendation Headline | Failure Mode Id | Recommended Interval | Recommended Resource Description | Total Unmitigated Risk | Total Mitigated Risk | Current Maintenance Task | Current Task Interval | Current Risk | Risk Delta (Current Risk-Total Mitigated Risk) | Change Level |
|---|---|---|---|---|---|---|---|---|---|---|
| CBM: Perform Weak Cylinder Test | 02.01.01. HP Fuel pump internal seals worn | 3 Months | Diesel Mechanic | 0.251 | 0.05 | SCH: HP Pump Replacement | 11000 MWHrs | 0.05 | 0 | Minor |
| SCH: Air-to-air intercooler overhaul: Interval to be established by age exploration. | 11.02.06. Air based intercooler leaking boost air due to fatigue cracking or erosion. | | Diesel Mechanic | 0.251 | 0.05 | NSM: Run to failure. | N/A | 0.05 | 0 | Moderate |
| CBM: Drain a small amount of fuel from the bottom of the fuel tank to check for water. | 01.08.01. Moisture condenses in the fuel tank, contaminating the fuel | 6 Months | Diesel Mechanic | 25.1 | 5 | NSM: Run to fail | N/A | 25.1 | 20.1 | Minor |
| CBM: Inspect turbocharger discharge piping for leaks while the locomotive is self-loading. | 11.02.01. Turbo discharge o-ring leaking boost air | 3 Months | Diesel Mechanic | 0.502 | 0.1 | CBM: Inspect turbocharger discharge piping for leaks while the locomotive is self-loading. | 4 months | 0.1 | 0 | None |
| | 11.02.09. WBIC inlet flange o-ring leaking | | | | | | | | | |
| CBM: Oil analysis | 02.02.04. Fuel Pump Roller Cracked | 7 Days | Oil Analysis | 203.61 | 107.2 | CBM: Oil Analysis | 7 Days | 107.2 | 0 | None |
| | 06.01.02. Piston and Cylinder seizure due to oil starvation | | | | | | | | | |
| | 07.01.07. Crosshead roller cracked due to introduced defect | | | | | | | | | |
| | 08.02.01. Bearing seizure due to cavitation damage | | | | | | | | | |
| | 08.02.05. Bearing failure due to assembly error | | | | | | | | | |
| | 09.01.01. Cylinder liner accelerated wear | | | | | | | | | |
| | 10.01.01. Cylinder liner perforation due to cavitation corrosion | | | | | | | | | |
| | 10.01.03. Cylinder liner shoulder seal fails prematurely | | | | | | | | | |
| DSN: Install water separator, alarm and dehumidifier breather in low pressure fuel system. | 01.08.01. Moisture condenses in the fuel tank, contaminating the fuel | | | 25.1 | 0.251 | NSM: Run to fail | N/A | 25.1 | 24.849 | Moderate |
| DSN: Redesign to use either hard piping or secure the hose in a suitable manner. | 04.01.01. Flexible Fuel return hose rubs through against compressed air pipe below the platform level | | | 50.2 | 25.35 | CBM: Detailed hose inspection for wear and rubbing | 4 months | 25.35 | 0 | Moderate |
| NSM: Run to fail, redesign may be desirable. | 07.01.01. Pushrod snapped. Root cause unknown. | | | 10 | 10 | NSM: Run to fail | N/A | 10 | 0 | None |
| PROC: Procedure to specify critical inspection locations | 04.01.01. Flexible Fuel return hose rubs through against compressed air pipe below the platform level | | | 60.5 | 15.15 | CBM: Detailed hose inspection for wear and rubbing | 4 months | 60.5 | 45.35 | Minor |
| | 04.01.02. Hose rubs through due to contact on another component combined with vibration | | | | | | | | | |
| | 04.01.03. Rubber hose cracks or splits due to perished rubber | | | | | | | | | |

Figure 5.10: Notable recommendations, part 1

| Recommendation Headline | Failure Mode Id | Recommended Interval | Recommended Resource Description | Total Unmitigated Risk | Total Mitigated Risk | Current Maintenance Task | Current Task Interval | Current Risk | Risk Delta (Current Risk-Total Mitigated Risk) | Change Level |
|---|---|---|---|---|---|---|---|---|---|---|
| SCH: HP Pump Replacement | 02.01.01. HP Fuel pump internal seals worn | 17000 MWhrs | Diesel Mechanic | 12.761 | 1.05 | SCH: HP Pump Replacement | 11000 MWHrs | 1.05 | 0 | Moderate |
| | 02.02.01. HP pump seizes | | | | | | | | | |
| | 02.02.05. Pump roller return spring breaks due to fatigue | | | | | | | | | |
| SCH: SCHeduled Injector replacement | 03.02.01. Injector atomising nozzles worn | 7000 MWHrs | Diesel Mechanic | 93.081 | 22.05 | SCH: Scheduled Injector replacement | 7000 MWHrs | 22.05 | 0 | None |
| | 03.03.01. Injector needle lift pressure low due to broken or softened spring | | | | | | | | | |
| | 03.03.02. Injector needle seizes due to excessive wear | | | | | | | | | |
| | 03.03.03. Injector needle, seat, pressure pin worn. | | | | | | | | | |
| | 03.03.04. Needle and seat degraded | | | | | | | | | |
| | 04.01.04. Injector O-Rings leaking | | | | | | | | | |
| SCH: Fuel Transfer Pump Replacement | 01.01.01. Fuel transfer pump fails | 17000 MWhrs | Diesel Mechanic | 2.51 | 0.251 | SCH: Fuel transfer pump replacement | 11000 MWHrs | 0.251 | 0 | Moderate |
| SCH: Lubricating oil to be replaced at 6 month intervals. | 09.02.09. Valve stem seizure due to gum build-up due to degraded lubricating oil. | 6 Months | Diesel Mechanic | 10 | 5 | SCH: Lubricating oil to be replaced at 6 month intervals. | 4 months | 5 | 0 | Minor |
| SCH: Replace the air-to-air fan bearings | 11.03.01. Air based intercooler fan bearings seized | 33750 MWHrs | Diesel Mechanic | 2.51 | 0.5 | NSM: Run to failure. | N/A | 2.51 | 2.01 | Moderate |
| SCH: Replace the air-to-air fan motor | 11.03.02. Air based intercooler fan failed; insulation broken down causing a ground fault. | 33750 MWHrs | Electrician | 2.51 | 0.5 | NSM: Run to failure. | N/A | 2.51 | 2.01 | Moderate |
| SCH: Replace the baggy air filters | 11.01.08. Baggy air filter clogged | 6 Months | Diesel Mechanic | 100 | 5 | SCH: Replace the baggy air filters | 4 months | 5 | 0 | Minor |
| SCH: Scheduled Injector replacement | 03.02.03. Injector seals worn allowing excessive back leagage | 7000 MWHrs | Diesel Mechanic | 2.51 | 0.5 | SCH: Scheduled Injector replacement | 7000 MWHrs | 0.5 | 0 | None |

Figure 5.11: Notable recommendations, part 2

| Failure Mode Id | Current Maintenance Task | Recommendation Headline |
|---|---|---|
| 01.08.01. Moisture condenses in the fuel tank, contaminating the fuel | NSM: Run to fail | DSN: Install water separator, alarm and dehumidifier breather in low pressure fuel system. |
| 11.02.06. Air based intercooler leaking boost air due to fatigue cracking or erosion. | NSM: Run to failure. | CBM: Air-to-air intercooler overhaul - Interval to be established by age exploration. |
| 11.02.07. 8.5" Aluminium Air to Air Intercooler Inlet flange cracked due to fatigue | NSM: Run to failure. | DSN: Replace the flanges on 8140-8156 with an upgraded, thicker version. |
| 11.03.01. Air based intercooler fan bearings seized | NSM: Run to failure. | SCH: Replace the air-to-air fan bearings |
| 11.03.02. Air based intercooler fan failed; insulation broken down causing a ground fault. | NSM: Run to failure. | SCH: Replace the air-to-air fan motor |

Figure 5.12: Recommendations applied to failure modes that are not currently addressed

## 5.5 Chapter Summary

This chapter has presented a complete summary of the functions identified by the analysis, an extract of the failure modes, failure effects and failure consequences identified by the analysis and an extract of the maintenance recommendations generated by the analysis, including a comparison with the current equivalent maintenance tasks.

The failure modes, failure effects, failure consequences and the recommendations that are presented in chapter 5 will be discussed further in chapter 6.

# Chapter 6

# Discussion of Results

## 6.1 Chapter Overview

This chapter provides a discussion on the RCM analysis preparation, process and results.

## 6.2 Key findings summary and discussion

### 6.2.1 HP fuel pump service life extension

HP fuel pumps have been identified as having exceptional performance; there have only been ten known failures (of which three were verified to be a manufacturing defect) since the introduction of the first 40 Evolution locomotives in 2008. The fleet size has steadily increased to 106 in 2014, equating to 1,272 high pressure pumps currently in service. The assessment of a life extension requires analysis of:

- Estimated failure rates
- The failure modes, effects and consequences
- Component condition inspection

The manufacturer's recommended service life is 13,000 MWHrs (GE Transportation 2012*d*, pg. 3), and the current maintenance interval is set at 11,000 MWHrs to align with a one-third engine life replacement (which equates to approximately 2.5 years, based on 350 MWHrs per month). The reliability modelling conducted, excluding the known manufacturing faults, indicates that 0.43% of the population (5.5 pumps) will fail prior to 11,000MWHrs, equating to a failure rate of 0.172% per year (2.2 pumps per year). If the service interval is extended to 17,000MWHrs, or four years, (a 55% increase on current life, but only a 31% increase on the OEM recommendation), 2.1% of pumps (26.7 pumps) will fail prior to overhaul, equating to a failure rate of 0.53% (6.7 pumps) per year.

Currently, RTIO does not have data on which failure modes will occur under an extended service life so that the failure effects and consequences can be assessed. However, based on the FMEA analysis (figures 5.3 to 5.5), the failure modes likely to occur can be assessed. The FMEA analysis found three failure modes that are likely to generate secondary damage to the engine:

- Failure mode 02.01.03, the roller guide pin failure.
  - This is a manufacturing defect that has been corrected.
- Failre mode 02.01.04, Roller cracking.
  - This failure mode can cause secondary damage to the cam section.
- Failure mode 02.01.05, Return spring cracking.
  - This will cause damage to the cam section and introduce metal debris to the lubricating oil, although debris will be removed by the filtration system.

These failure modes are uncommon based on the current maintenance strategy, but may become more prevalent if the service life is extended. For this reason, age exploration is considered critical to make an informed decision regarding the optimum service life.

Age exploration of the HP fuel pump was planned to be completed during the project but spare part availability prevented the tests from being completed. The method would be to remove and examine pump condition at 11,000MWHrs, 13,000MWHrs, 14,000MWHrs, 15,000MWHrs, 16,00MWHrs and 17,000MWHrs.

The analysis identified that RTIO does not currently perform a Weak Cylinder Detection test, which can provide a condition assessment of the pump performance at locomotive scheduled services to support the age exploration exercise. RTIO currently uses the Dead Cylinder Detection test (DCD) but does not perform the WCD.

The author believes that the analysis shows that further investigation is warranted to evaluate a life extension to the HP fuel pump.

### 6.2.2 Injector findings

Along with HP fuel pumps, fuel injectors were identified early on in the project as having very few in-service failures, making them a possible candidate for life extension. However, testing revealed very poor performance of injectors at the end of their current service life (section 3.10.2), which is very concerning and will instigate a Defect Elimination (DE) project to determine the reason for the poor performance. Interestingly, the majority of the failure modes identified for injectors were wear-out patterns, but the reliability modelling indicated that the injector is experiencing an early-life failure pattern. An early-life failure pattern indicates that the poor injector performance cannot be countered by a reduced service life. At this point, no change is recommended to the injector service life.

### 6.2.3 Fuel transfer pump service life extension

As noted in section 6.3.3, the individual failure modes for the fuel transfer pump (FTP) are not known; however, modelling the entire failure dataset using RTRS showed that as a 'black-box' unit, the pump displays a wear-out pattern. The dominant failure mode is understood to be due to a design issue; the hot return fuel enters the tank next to the fuel intake, causing the fuel transfer pump inverter to overheat (failure mode 01.07.02., figure 5.3).

A service interval optimisation was performed using RTRS (refer to figure 3.9). The unplanned cost of replacement was estimated to be double the cost of planned replacement, based on a four hour delay due to locomotive failure when the fuel pump fails. The optimisation indicated that the best pump replacement interval is 4.5 years, which is slightly more than half engine life (16,875 MWHrs) as opposed to the OEM recommendation of engine life (33,750 MWHrs) (GE Transportation 2012*d*, pg. 3) and the current maintenance strategy of 11,000MWHrs (one third engine life).

### 6.2.4 Servicing Interval

Currently, locomotives are given a full service at 4 month intervals. RTIO is in the process of managing a change to a six monthly service intervals with a three monthly interim inspection. This initiative did not originate from the RCM analysis, but the analysis has identified failure modes that need to be addressed at the 3 month interim service and those that can be extended to the 6 monthly full service.

The analysis has identified that the current servicing regime, as far as the engine subsystems that have been analysed are concerned, is over-maintaining the equipment. For example:

- Fuel filters are rated to 6 months service (GE Transportation 2012*c*, pg. 6) but RTIO replaces them at 4 month intervals (GE Transportation 2012*c*, pg. 6).
- Baggy air filters are currently replaced at 4 monthly intervals, but a 6-month service life filter is available (see figure 5.7, failure mode 11.01.08).

### 6.2.5 Condition Monitoring using Acoustic Emissions Analysis

The literature review conducted on condition monitoring revealed Acoustic Emissions (AE) analysis as a potential condition monitoring tool. The RCM analysis identified that AE could address the following failure modes:

- 02.01.01. HP pump seizes.
- 02.02.01. HP fuel pump internal seals worn.
- 03.02.02. Injector nozzle blocked or partially blocked due to carbon build up.
- 03.03.01. Injector needle lift pressure low due to broken or softened spring.
- 03.03.03. Injector needle, seat, and pressure pin worn.

- 03.03.02. Injector needle seizes due to excessive wear.
- 09.02.04. Valve disc burnt due to insufficient valve lash.
- 09.02.05. Valve fatigue fracture due to excessive valve lash.

AE would not completely eliminate any maintenance tasks, but may enable them to become condition-based rather than scheduled, reducing the overall maintenance cost. The maintenance tasks affected are discussed below.

**Scheduled HP fuel pump replacement**

The scheduled HP fuel pump replacement would become a condition-based task. The modelling conducted (reference section 6.2.1 and figure 3.6) and the FMEA indicate that the HP fuel pumps have a strong wear-out failure pattern. 2.1% of pumps will fail by half engine life (17,000MWHrs, 4 years); however, if the fuel pumps are run for the entire life, 20% of the population will fail prior to the end of engine life (33,750MWHrs, 8 years), indicating that AE has the potential to allow 80% of the fuel pumps to run for the entire engine life. However, the author notes that the data available to support this position is minimal, and age exploration and component inspection is required to understand which failure modes (that are currently masked by the current maintenance strategy) will occur.

The three pump failure modes identified as having the potential to cause secondary damage in section 6.2.1 are not mitigated by AE. The possibility of these failure modes occurring over the life of an engine is considered to be out of the scope of the research project, but this work must be completed prior to implementing an AE condition monitoring program, as it could allow serious failures to occur without any proactive maintenance actions.

Further work required to implement an AE program includes the evaluation of the P-F interval of each failure mode, which is considered to be out of the scope of this research project. It has been identified that the P-F interval of each failure mode must be greater than 6 months (the future scheduled maintenance interval) such that potential fuel pump failures could be planned for completion at the next scheduled maintenance interval. Constantly removing the locomotive from service outside of standard servicing to replace a fuel pump is a logistically costly exercise (refer to section 3.6).

#### Scheduled injector replacement

AE has shown the ability to detect injector malfunction, enabling injectors to be replaced on-condition. Injectors have a shorter life span than HP fuel pumps - an engine will consume approximately 5 sets of injectors between overhauls - so the likelihood of being able to reduce injector consumption is higher.

The P-F interval is critical and must be greater than 6 months, as discussed regarding the HP fuel pumps, but the author has not been able to complete this work. The P-F interval is particularly important because injector faults can be more sinister than high pressure pump faults. Leaking injectors can cause piston holing, injectors that do not atomise fuel can cause lubrication failure of the piston/cylinder interface, and both can cause fuel dilution.

#### Scheduled valve lash inspection

AE can detect an incorrect valve lash, so valve lash inspection can be performed by the AE system instead of a mechanic. This is a small saving, as valve lash inspection accounts for approximately 2 hours of labour per locomotive per year.

#### Weak cylinder testing

AE can detect weak cylinders so there would be no need to run the weak cylinder detection test, which RTIO does not currently perform.

### 6.2.6 Flexible hose inspection process

Flexible hose failure is a risk that has been captured in the analysis (failure modes 04.01.01 to 04.01.03). The current service procedure requires that flexible fuel hoses should be checked for damage but does not specify which hoses should be checked or the critical locations. A significant fuel spill has occurred due to a flexible hose rub;

this analysis has identified that a lack of process control on the hose inspection may leave the business exposed to risk in the future. A more robust process would be to specify the flexible hoses and critical locations that require careful inspection.

### 6.2.7 Crankcase inspection

A crankcase inspection is currently performed to check for a number of failure modes at a four-monthly interval, compared to the OEM recommended inspection interval of twelve-monthly (GE Transportation 2012*c*, pg. 6). The failure modes are listed in table 6.1, along with an estimate of the P-F interval obtained by discussion with experienced engineers and tradespeople. The table shows that the P-F interval for most of the failure modes is much shorter than the inspection period, meaning that the inspection task is not 'worth doing' (Moubray 2001, pg. 146) (for further context, refer to section 2.5.8). Additionally, there are alternative maintenance tasks that are 'worth doing', indicating that the crankcase inspection does not contribute much to the asset reliability.

Even though the crankcase inspection cannot be relied upon as an effective maintenance task, it can still be partially effective. Not all failures will be detected, but statistical probability dictates that a proportion of failures will be detected, depending on the P-F interval length of the specific failure mode. The inspection also provides the tradesperson with the advantage of internal engine component familiarity; this familiarity aids the tradesperson when troubleshooting engine faults, such as abnormal oil analysis results or crankcase overpressure events.

Even though the crankcase inspection is not a robust maintenance task, the inspection task still reduces the risk of failure enough to be 'worth doing' due to the low cost and negligible impact on asset availability.

### 6.2.8 Cracked pushrods

Five locomotives have experienced a cracked pushrod (see figure 5.7, failure mode 07.01.01.). It is an uncommon failure mode and the root cause is not understood. When modelled against the Weibull distribution (refer to figure 3.15 and 3.15), the

Table 6.1: Failure modes addressed by the crankcase inspection

| Failure Mode | P-F Interval, approximate | Alternative maintenance task |
|---|---|---|
| Coolant leaks; 10.01.03. Cylinder liner shoulder seal fails prematurely, 10.01.01. Cylinder liner perforation due to cavitation corrosion | 12 Months | Spectrographic oil analysis |
| Bearing faults; 08.02.02. Bearing failure due to fatigue cracking, 08.02.01. Bearing seizure due to cavitation damage | 2 Weeks | Spectrographic oil analysis |
| Worn or distressed camshaft lobes and rollers; 02.01.04. Fuel Pump Roller Cracked, 07.01.08. Crosshead roller cracked due to fatigue | 6 months | Spectrographic oil analysis |
| Scored liners; 06.01.08. Piston/cylinder liner scoring. Root cause unknown. | 6 Months | Spectrographic oil analysis |
| Cracked liners; 06.01.01. Cylinder liner failure due to fatigue cracking | 2 Weeks | Scheduled replacement, Spectrographic oil analysis |
| Piston wear and seizure; 06.01.02. Piston and Cylinder seizure due to oil starvation, 06.01.04. Piston skirt wear allowing misalignment and overloading | 6 Months | Spectrographic oil analysis |
| Signs of localised overheating; 06.01.11. Piston component seizure due to overheating | 3 Months | Spectrographic oil analysis |
| Loose or missing components | 2 Weeks | N/A |
| Cracked components; 08.01.02. Premature connecting rod fatigue failure, 06.01.03. Piston failure due to fatigue cracking | 1 Week | N/A |

failure pattern was found to be random. A 'run-to-failure' recommendation is proposed for the following reasons:

- The failure pattern is random; scheduled replacement is 'technically feasible' but not 'worth doing' because pushrods failures are not age-related.
- The project was unable to identify a 'technically feasible' inspection process to support a condition-based maintenance tactic.

### 6.2.9 Turbo discharge O-rings

The high consumption rate of turbo discharge O-rings was identified in section 3.12.5. The analysis process found that while these O-rings are failing regularly, they do not cause any significant problems. As such, a run to failure recommendation has been put forward.

### 6.2.10 Identification of failure modes that are not currently addressed by a maintenance tactic

The project identified very few failure modes that are not addressed by an appropriate maintenance strategy. They are presented in figure 5.12 and discussed in the following paragraphs.

#### Fuel tank water condensation

The locomotive maintenance regime does not currently include a task to check for water contamination by condensation (failure mode 01.08.01), nor is there an on-board water separator. There does not appear to be a record of water condensation problem in the maintenance history, but water ingress is considered a risk. As such, the recommendation in the analysis has been made to check the fuel tank for water condensation every six months or to install a dehumidifying breather, water separator and alarm.

**Air-based intercooler inlet flange cracking**

The air-based intercooler inlet flange is suffering cracking across 17 locomotives delivered in 2009 and 2010 (refer to figure 5.8, failure mode 11.02.07). The failure causes boost air leakage and causes the locomotive to derate. The reliability analysis used the Weibull distribution to determine the flanges became more unreliable with age (section 3.12.1). The author found that the OEM had upgraded the flange, so the recommendation is put forward to replace the flanges on the 17 at-risk locomotives and upgrade the flanges on the rest of the fleet at engine change.

**Air-based intercooler and fans overhaul**

RTIO currently has no maintenance strategy applied to the air-based intercooler; the OEM recommends that the air-based intercooler is replaced at engine overhaul (GE Transportation 2012*d*, pg. 2). The analysis found that the consequences of intercooler failure is quite low (see figures 5.8 and 5.9), as the locomotive is likely to only derate (not fail) and no secondary damage will be caused. However, it is likely that the intercooler failures will be age-related due to vibration causing fatigue failure. For this reason, it is recommended that the air-based intercoolers are subjected to 'age exploration' to determine the optimum overhaul interval. Naturally, this project could not incorporate age exploration because it will take a number of years to evaluate.

## 6.3 Assumptions, limitations and deviations from best practice

### 6.3.1 RCM working groups

The RCM analysis process involves five or six participants, including operators, maintainers, engineers and technical specialists (Moubray 2001, pg. 267). Moubray (2001, pg. 101, 286-290) advises against performing the analysis in isolation. Unfortunately, the author was not able to engage a working group for the analysis due to resource constraints, so the bulk of the analysis was created without a team. To mitigate this limitation, the author consulted senior tradesmen during the development of the Failure Modes and Effects Analysis (FMEA) (see appendix H for the RCM introduction presentation) and senior engineers were consulted for review of the analysis once completed.

Train drivers were not involved in the analysis which, on a surface level, contradicts the literature (section 2.5.10). However, the author interprets the literature to refer to operators that are responsible for directly operating the plant, thus having an intimate knowledge of the operating behaviour and procedures of the plant. The locomotive engine is operated indirectly; it is directly controlled by the Engine Control Unit (ECU). Consequently, train drivers have very little knowledge of engine failure modes and are more concerned with controlling in-train forces and obeying track speeds and signals; therefore, they cannot participate meaningfully in an RCM/FMEA analysis.

### 6.3.2 Calculation of task intervals

Moubray (2001, pg. 286-290) warns that if the manufacturer's recommendations are relied upon, the RCM analysis effectiveness can be compromised. The author has challenged a number of maintenance tasks and task intervals, however, the author was unable to calculate the optimum task intervals for some recommendations. For example, calculating the fatigue life of engine components, the P-F interval of main bearing failure modes, or the correct interval at which to check the valve lash would be very time-consuming, detracting from the rest of the analysis. Additionally, 'age exploration' of critical components to determine the optimum interval is considered prohibitively risky. In these instances, the OEM recommended intervals have been accepted, and the author has taken the approach of identifying the failure modes, failure effects and failure consequences to justify the maintenance task cost.

### 6.3.3 Weibull distribution modelling

The Weibull distribution should be applied to individual failure modes (Abernethy 2006, pg. 1.4)); however, the author found it necessary to apply the Weibull distribution using poor quality data. This was performed on the HP fuel pumps, injectors and fuel transfer pump. The HP pump failure mode data had not been systematically recorded; in some cases, the failure mode may not be readily discernable. The fuel transfer pump data suffered the same problem, but in a more exaggerated manner; there was no identification of the failure mode available because the failure mode is never diagnosed by RTIO personnel. The decision was taken to model the components despite the data inadequacies, with the goal of obtaining at least some indication of the dominant failure mode pattern. The author believes this added value when assessing optimum maintenance intervals.

## 6.4 Chapter Summary

The discussion has provided the reader with further details and context surrounding the key findings from the RCM analysis.

# Chapter 7

# Conclusions and Further Work

This chapter presents the project conclusions, achievements and work that has been identified for future endeavour.

## 7.1 Achievement of Project Objectives

The primary research aim, as detailed in the project specification (appendix A) and the research aims and objectives (section 1.2) is to assess whether the current locomotive engine maintenance regime is optimised and to develop and document the knowledge of the failure modes and risk mitigated by each maintenance task.

- The project has established that the current maintenance regime applied to the RTIO locomotive engine fuel system, power assemblies and combustion air system is generally optimised, but a small number of opportunities to improve have been identified. Table 5.1 shows that most maintenance tasks require no change and no major changes are recommended. A full summary of the recommendations and comparison to the current maintenance tactics is included in appendix K.
- The project has successfully developed a database of the RTIO Evolution locomotive diesel engine functions, failure modes, failure effects, failure consequences, maintenance tactic recommendations and redesign opportunities. This database inherently produces justification for each maintenance task according to the failure modes it addresses and clearly presents the risk that is mitigated by each

maintenance task. Within RTIO, it is stored in a user-friendly database with an intuitive interface; to accompany this dissertation, an exported version of the database is provided in mayne_caleb_goh_rcm_data.xls.

The research objectives underpinning the primary research aim, as detailed in section 1.2, have been addressed and the conclusions presented below:

1. **Identification of excess maintenance, inadequate maintenance and undocumented failure modes.** Areas of excess maintenance and inadequate maintenance are identified in the recommendations results (figures 5.10 to 5.11 and appendix K) by the change level. Important recommendations are discussed in section 6.2. The project searched for failure modes that are undocumented or not addressed by a documented maintenance tactic and found only three items that are not appropriately addressed by a maintenance tactic (refer to section 6.2.10). The senior technicians did not identify any 'unofficial' maintenance tasks.

2. **Failure modes, failure effects and failure consequences analysis.** The RCM analysis has documented 120 distinct failure modes (section 5.3), evaluated the failure effects and assessed the consequences. Information sources included senior tradespeople, historical maintenance records and diesel engine literature (section 4.2.3). This has provided a basis to recommend maintenance tactics that are 'technically feasible' and 'worth doing', which are presented in chapter 5 and discussed in chapter 6.

3. **Assessment of condition monitoring technology opportunities.** Heavy diesel engine condition monitoring techniques were presented in section 2.6. Oil analysis was found to be highly applicable and, based on the RCM analysis, it is recommended that the current oil analysis program is continued. Acoustic Emissions (AE) analysis is discussed further in section 6.2.5; AE is capable of detecting a number of failure modes related to the fuel system and power assembly. The analysis has found that an AE monitoring program is unlikely to detect all the possible failure modes for any one component and that for the failure modes it can detect, the P-F interval will require costly, and potentially risky, robust evaluation. The author was not able to evaluate this data during the project. For these reasons, AE is not recommended as RTIO is not currently ready to make a significant commitment to an AE program. Other condition monitoring

techniques were investigated but the analysis did not find any application for these techniques.

4. **Establish failure mode service life characteristics.** Weibull analysis has been applied to a number of components and failure modes, providing valuable information for tactic recommendation (reference sections 6.2.1, 6.2.2, 6.2.3 and 6.2.8). Some of the analyses are subject to data limitations and assumptions that are detailed in section 6.3.3.

5. **Engine system identification and prioritisation.** The engine systems were identified and prioritised in sections 3.4 and 3.5. The definition and prioritisation process provided the necessary clarity and direction for the RCM analysis.

6. **Operating context definition.** The locomotive operating context has been documented in section 3.6, providing a reference point to underpin the evaluation of failure effects and failure consequences.

The project specification program (contained in appendix A) has been fulfilled as follows:

1. The literature on diesel engine maintenance has been reviewed and presented in section 2.2.

2. Diesel engine condition monitoring technology has been reviewed and presented in section 2.6.

3. The primary engine systems for power production are defined in section 3.4.

4. A criticality analysis and prioritisation of each engine system is presented in section 3.5.

5. The author engaged working groups and individuals formally and informally to add detail and validate the analysis, as discussed in section 6.3.1. Senior mechanical technicians participated in FMEA sessions for each of the analysed engine subsystems. The sessions were aimed at capturing undocumented failure modes and providing an experienced assessment of failure effects. The sessions were very informative and provided 'front-line' information that could not have been gained any other way.

6. The functional analysis has been conducted as per chapter 4, section 4.2.1 and the results are presented in section 5.2.

7. The functional failures have been identified as per section 4.2.2 and presented in section 5.2.

8. The failure modes, failure effects and failure consequences are identified as per sections 4.2.3 and 4.2.4; a detailed extract is presented in section 5.3, a complete list of the short descriptions is presented in appendix J and the entire dataset is included in the excel file accompanying this dissertation, mayne_caleb_goh_rcm_data.xls.

9. Proactive maintenance task proposals are developed as per section 4.2.5 and the results are presented in section 5.4. The important recommended changes are presented in figures 5.10 and 5.11 and discussed in section 6.2, providing clear identification of items that are over-maintained and under-maintained. The complete list of recommendations is included in appendix K.

10. A comparison of the proposed maintenance tasks with the current maintenance program is presented in section 5.4.

## 7.2 Further Work

**Fuel injector performance** A defect elimination project will be required to determine the appropriate root cause of the poor fuel injector performance.

**HP fuel pump life extension** The project was not able to perform an age exploration exercise to verify pump performance. This will need to be executed to ensure the validity of the recommendations in this project.

**Acoustic Emissions Analysis** If the business decides to pursue AE analysis, a robust evaluation of the P-F interval of HP pump failures and injector failures is required to assess whether AE can provide a positive benefit.

**Further engine subsystem analysis** The project has analysed engine subsystems according to the prioritisation exercise in section 3.5; only the top 3 subsystems have been analysed. The following systems still require analysis:

- Bottom end

- Engine sensors
- Cooling system
- Lubricating oil system
- Exhaust air system

## 7.3 Project Reflection

The author's initial understanding of how the project is valuable in both an academic research sense and industry outcomes sense was incomplete, in that he expected the extent of the project requirements to be the completion of some 'unique' work that was grounded in a sound methodology. However, as the project 'journey' progressed, the author found satisfaction in understanding how the project contributes to the body of knowledge in academia and industry.

During the early stages of the research project, the author treated the literature review as the precursor to developing the methodology which, in this case, is how to apply the RCM methodology. While this is important, the author learnt that the literature also needs to inform and aid the development of the research questions, which forms the basis for academic research. Learning the process of using literature to identify academic knowledge gaps and inform the research questions has given the author the opportunity to develop the skills to complete academically robust research.

The author also learnt to differentiate between academic research and industry outcomes. Academic research questions are driven by identifying a gap in academic literature, while industrial enterprises naturally require the application of knowledge to improve profitability in some way. The confluence of these concepts has, in the author's opinion, created an interesting project that has achievements in the areas of academia, industry and the author's professional competencies.

The author believes that the project has achieved in two areas; firstly, the learning outcomes discussed above and, secondly, the fulfillment of the project objectives. The primary research aims include the assessment of the optimisation of the current maintenance regime applied to the locomotive engine and the development of a database that justifies each maintenance task by documenting the failure mode and risks that are mitigated by each maintenance task (refer to Appendix A and section 1.2 for further discussion on the research aims). The author is confident that the learning outcomes, research aims and project objectives have been fulfilled.

# References


Abernethy, R. (2006), *The New Weibull Handbook: Reliability and Statistical Analysis for Predicting Life, Safety, Supportability, Risk, Cost and Warranty Claims*, Barringer & Associates, Florida, USA.

Albarbar, A., Gu, F. & Ball, A. (2010), 'Diesel engine fuel injection monitoring using acoustic measurements and independent component analysis', *Measurement* **43**(10), 1376–1386.

Arcidiacono, G. & Campatelli, G. (2004), 'Reliability improvement of a diesel engine using the fmeta approach', *Quality and Reliability Engineering International* **20**(2), 143–154.

Asi, O. (2006), 'Failure of a diesel engine injector nozzle by cavitation damage', *Engineering Failure Analysis* **13**(7), 1126–1133.

Askeland, D. R. & Phulé, P. P. (2006), *The science and engineering of materials*, Thomson, Ontario, Canada.

Bejger, A. (2011), 'Analysis of damage of selected elements of the injection system of marine diesel engines', *Journal of Polish CIMAC* **6**, 23–30.

Bertling, L., Allan, R. & Eriksson, R. (2005), 'A reliability-centered asset maintenance method for assessing the impact of maintenance in power distribution systems', *Power Systems, IEEE Transactions on* **20**(1), 75–82.

Besnard, F., Fischer, K. & Bertling, L. (2010), Reliability-centred asset maintenance a step towards enhanced reliability, availability, and profitability of wind power plants, *in* 'Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES', IEEE, pp. 1–8.

Carretero, J., Prez, J. M., Garca-Carballeira, F., Caldern, A., Fernndez, J., Garca, J. D., Lozano, A., Cardona, L., Cotaina, N. & Prete, P. (2003), 'Applying rcm in large scale systems: a case study with railway networks', *Reliability Engineering and System Safety* **82**(3), 257–273.

Chen, Y. & Zhu, W.-h. (2008), 'Application of RCM in Dayabay nuclear power station', *Electrical Equipment* **9**(12), 113–116.

Cummins Filtration (2014), 'The complete guide to fluid analysis', http://www.cumminsfiltration.com. Accessed on 22 June 2014.

Dempsey, P. (2008), *Troubleshooting & Repairing Diesel Engines*, McGraw-Hill.

Deshpande, V. & Modak, J. (2002), 'Application of rcm for safety considerations in a steel plant', *Reliability Engineering and System Safety* **78**(3), 325–334.

Deshpande, V. & Modak, J. (2002b), 'Application of rcm to a medium scale industry', *Reliability Engineering and System Safety* **77**(1), 31–43.

Douglas, R., Steel, J. & Reuben, R. (2006), 'A study of the tribological behaviour of piston ring/cylinder liner interaction in diesel engines using acoustic emission', *Tribology International* **39**(12), 1634–1642.

Elamin, F., Fan, Y., Gu, F. & Ball, A. (2009), 'Detection of diesel engine valve clearance by acoustic emission.', University of Huddersfield. Huddersfield, UK.

Elamin, F., Gu, F. & Ball, A. (2010), 'Diesel engine injector faults detection using acoustic emissions technique', *Modern Applied Science* **4**(9), p3.

Fynn, C., Basson, M., Sinkoff, S., Moubray, A. & Nadeau, R. (2007), *Applicability of reliability-centered maintenance in the water industry*, American Water Works Association.

Gabbar, H. A., Yamashita, H., Suzuki, K. & Shimada, Y. (2003), 'Computer-aided rcm-based plant maintenance management system', *Robotics and Computer-Integrated Manufacturing* **19**(5), 449–458.

GE Transportation (2012*a*), *GE Evolution Series Level 2 - 12 Cylinder GEVO Diesel Engine Running Repair and Maintenance*, General Electric Transportation, Erie, Pennsylvania, USA.

GE Transportation (2012*b*), *GEK-114239U GEVO Diesel Engine Maintenance*, GE Transportation, Erie, Pennsylvania, USA.

GE Transportation (2012*c*), *GEK-114307D Scheduled Maintenance, Rio Tinto 12-Cylinder Evolution Series Locomotive*, GE Transportation, Erie, Pennsylvania, USA.

GE Transportation (2012*d*), *GEK-76667-P Component Overhaul Schedule, Evolution Series Locomotive*, GE Transportation, Erie, Pennsylvania, USA.

GE Transportation (2012*e*), *Training Manual, Evolution Series Locomotive Mechanical Systems: Level 2*, General Electric Transportation, Erie, Pennsylvania, USA.

GE Transportation (2014), *Diesel Engine - Renewal Parts Catalogue*, Renewal Parts Catalogue, GE Transportation, Erie, Pennsylvania, USA.

Greuter, E. & Zima, S. (2012), *Engine Failure Analysis: Internal Combustion Engine Failures and Their Causes*, SAE International, Pennsylvania, USA.

Gu, Y.-k. & Yang, Z.-Y. (2007), Ts-neural-network-based maintenance decision model for diesel engine, *in* 'Advances in Neural Networks–ISNN 2007', Springer, pp. 553–561.

Hauge, B. S., Stevens, A. M., Loomis Jr, R. & Ghose, A. (2000), Reliability-centered maintenance on the space shuttle program, *in* 'Reliability and Maintainability Symposium, 2000. Proceedings. Annual', IEEE, pp. 311–316.

Hercamp, R. D. (1993), 'An overview of cavitation corrosion of diesel cylinder liners', *ASTM SPECIAL TECHNICAL PUBLICATION* **1192**, 107–107.

Jardine, A. K., Lin, D. & Banjevic, D. (2006), 'A review on machinery diagnostics and prognostics implementing condition-based maintenance', *Mechanical systems and signal processing* **20**(7), 1483–1510.

Johnson, M. (2011), 'Wear debris measurement', *Mining and Metallurgy* (5), 27–34.

Kim, E. Y., Tan, A. C. & Yang, B.-S. (2012), Acoustic emission for diesel engine monitoring: a review and preliminary analysis, *in* 'Engineering Asset Management and Infrastructure Sustainability', Springer, pp. 489–499.

Kosel, T. (1992), 'Solid particle erosion', *ASM International* **18**, 199–213.

Liu, Y., Huang, H.-Z., Miao, Q. & Zuo, M. J. (2007), Analysis and evaluation of reliability of diesel engine based on maintenance records, *in* 'ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference', American Society of Mechanical Engineers, pp. 451–456.

Lodge, E. S. (1950), Diesel engine maintenance, Technical report, SAE Technical Paper.

Lowe, D. P. (2013), Characterisation of combustion related acoustic emission sources for diesel engine condition monitoring, PhD thesis, Queensland University of Technology, Queensland, Australia.

Macian, V., Payri, R., Tormos, B. e. a. & Montoro, L. (2006), 'Applying analytical ferrography as a technique to detect failures in diesel engine fuel injection systems', *Wear* **260**(4), 562–566.

Macian, V., Tormos, B., Olmeda, P. & Montoro, L. (2003), 'Analytical approach to wear rate determination for internal combustion engine condition monitoring based on oil analysis', *Tribology International* **36**(10), 771–776.

Martin, G. G. (2004), 'Failure of a stationary pump engine piston', *Journal of Failure Analysis and Prevention* **4**(1), 37–39.

Mba, D. & Rao, R. B. (2006), 'Development of acoustic emission technology for condition monitoring and diagnosis of rotating machines; bearings, pumps, gearboxes, engines and rotating structures', Cranfield University, UK.

Meridium (2012), *Meridium APM Help - Overview of Reliability Distribution Analysis*, Meridium Inc., Virginia, USA.

Meridium (2014), 'Meridium reliability centered maintenance & failure modes and effects analysis (rcm and fmea)', https://www.meridium.com/knowledge-center/meridium-reliability-centered-maintenance-failure-modes-and-effects-analysis-rcm. Accessed on 13 July 2014.

Milkie, C. & Perakis, A. N. (2004), 'Statistical methods for planning diesel engine overhauls in the us coast guard', *Naval engineers journal* **116**(2), 31–42.

Mollenhauer, K. & Tschke, H. (2010), *Handbook of diesel engines*, Springer, Berlin, Germany.

Moubray, J. (2001), *RCM II: reliability-centered maintenance*, Industrial Press Inc., New York, USA.

Netherton, D. (2002), Reliability centered maintenance, *in* 'ASM Handbook Failure Analysis and Prevention', Vol. 11, ASM International.

Nowlan, F. S. & Heap, H. F. (1978), Reliability-centered maintenance, Report, United Airlines, California, USA.

O'Connor, P. & Kleyner, A. (2011), *Practical reliability engineering*, John Wiley & Sons, West Sussex, UK.

Priest, M. & Taylor, C. (2000), 'Automobile engine tribology approaching the surface', *Wear* **241**(2), 193–203.

Procaccia, H., Lannoy, A. & Clarotti, C. (1997), Probabilistic risk analysis of aging components which fail on demand. a bayesian model. application to maintenance optimization of diesel engine linings, Technical report, Electricite de France (EDF), 92-Clamart (France). Direction des Etudes et Recherches.

Rabb, R. (1996), 'Fatigue failure of a connecting rod', *Engineering Failure Analysis* **3**(1), 13–28.

*Rail Safety Act* (2010). (State of Western Australia).

*Rail Safety Regulations* (2011). (State of Western Australia).

Rausand, M. (1998), 'Reliability centered maintenance', *Reliability Engineering and System Safety* **60**(2), 121–132.

Roylance, B. (2005), 'Ferrographythen and now', *Tribology International* **38**(10), 857–862.

Sharma, B. & Gandhi, O. (2008), 'Reliability analysis of engine oil using polygraph approach', *Industrial Lubrication and Tribology* **60**(4), 201–207.

Shuster, M., Mahler, F. & Crysler, D. (1999), 'Metallurgical and metrological examinations of the cylinder liner-piston ring surfaces after heavy duty diesel engine testing', *Tribology transactions* **42**(1), 116–125.

Silva, F. (2006), 'Fatigue on engine pistons–a compendium of case studies', *Engineering failure analysis* **13**(3), 480–492.

Smith, A. M. & Hinchcliffe, G. R. (2003), *RCM–Gateway to World Class Maintenance*, Butterworth-Heinemann, MA, USA.

Society of Automotive Engineers (2002), *A guide to the reliability centered maintenance (RCM) standard*, SAE Standard JA1012, Society of Automotive Engineers, Pennsylvania, USA.

Society of Automotive Engineers (2009), *Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes*, SAE Standard JA1011, Society of Automotive Engineers, Pennsylvania, USA.

Standards Australia (2006), *Railway safety management*, AS4292, Standards Australia, Sydney, Australia.

Standards Australia (2011), *Dependability management Part 3.11: Application guide Reliability centred maintenance*, AS IEC 60300.3.11, Standards Australia, Sydney, Australia.

Thomas, N. (2014), Interpreting routine oil analysis test results to optimise decision making, Report, Rio Tinto Iron Ore, Perth, Australia.

Unterweiser, F.R., Hutchings, P.M. (1981), 'Fatigue failure of a diesel engine piston pin', *ASM International* **11**.

Von Wielligh, A., Burger, N. & Wilcocks, T. (2003), 'Diesel engine failures due to combustion disturbances, caused by fuel with insufficient lubricity', *Industrial Lubrication and Tribology* **55**(2), 65–75.

Wang, Q. (1997), 'Seizure failure of journal-bearing conformal contacts', *Wear* **210**(1), 8–16.

Weibull, W. (1951), 'A statistical distribution of wide applicability', *Journal of applied mechanics* .

Windrock, Inc. (2013), 'Online monitoring systems', http://www.windrock.com/products/online-monitoring-systems/. Accessed on 12 July 2014.

Youngk, R. D. (2000), Automobile engine reliability, maintainability and oil maintenance, *in* 'Reliability and Maintainability Symposium, 2000. Proceedings. Annual', IEEE, pp. 94–99.

# Appendix A

# Project Specification

ENG 4111/2 Research Project

## Project Specification

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|---|---|
| For: | **Caleb Mayne** |
| Topic: | Reliability Centred Maintenance Analysis of a Rio Tinto Iron Ore Evolution Locomotive Engine |
| Supervisors: | Steven Goh<br>John McArthur (Locomotive Reliability Specialist, Rio Tinto Iron Ore) |
| Sponsorship: | Faculty of Health, Engineering & Sciences<br>Rio Tinto Iron Ore (RTIO) |
| Project Aim: | The project aims to establish whether RTIOs current maintenance regime is optimised and to develop and document the knowledge of the failure mode and risk mitigated by each maintenance task. |

Program:

1. Research maintenance and Reliability Centred Maintenance (RCM) related to large diesel engines, both in rail and other industries

2. Research condition monitoring technologies applied to large diesel engines that may be applicable to RTIO locomotives.

3. Identify the primary engine systems that are fundamental to the production of mechanical power and;

4. Perform a criticality analysis and prioritise the engine systems for analysis
   *As time permits, perform steps 5-10 for each engine system:*

5. The author will be required to develop the framework for the RCM analysis (items 6-10), and then engage working groups consisting of experienced tradespersons, technicians and engineers to add detail and validate the analysis

6. Identify the functions of each system

7. The ways in which the system can fail to fulfil these functions

8. Investigate the causes of the 'functional failures identified (failure modes), the failure effects and failure consequences

9. Propose maintenance tasks (predictive/preventive) to mitigate/counteract the failures where appropriate. If required, identify items that cannot be feasibly maintained and require redesign and propose solutions where possible

10. Compare the proposed maintenance tasks with the current maintenance program and evaluate the magnitude of the proposed changes

11. Compile and submit an academic dissertation on the project.

Agreed:

Student Name: Caleb Mayne
Date: 12 July 2014

Supervisor Name: Steven Goh
Date:

Examiner: Chris Snook
Date:

# Appendix B

# Subsystem Prioritisation Data

## B.1 Engine Subsystem Prioritisation Source Data

Appendix B contains samples of the raw data used to prioritise the engine subsystems.

| Bas. start date | Order | Functional Loc. | | Description | System | Order Type | TotalPlnndCost | Total act.costs | Notification | Created on | Description |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 05/12/2012 | 23111635 | 3076LOC8100 | | COP inductor boost flange adaptor mod | Bottom End | PM02 | 99.70 | 99.70 | 18617174 | 07/12/2012 | 8100 GE-EVO Locomotive |
| 18/05/2012 | 22857092 | 3076LOC8100 | | Check Eductor Boost & Turbo Supply Lines | Combustion Air System | PM02 | 49.85 | 49.85 | 17453845 | 18/05/2012 | 8100 GE-EVO Locomotive |
| 05/11/2012 | 23021492 | 3076LOC8100 | | Turbo Flex Duct Allignment | Combustion Air System | PM02 | 6,343.84 | 6,343.84 | 18200457 | 28/09/2012 | 8100 GE-EVO Locomotive |
| 01/04/2013 | 23267060 | 3076LOC8100 | | EVO 8" Air to Air duct FMI - Upgrade | Combustion Air System | PM02 | 514.36 | 257.18 | 19389385 | 04/04/2013 | 8100 GE-EVO Locomotive |
| 24/06/2013 | 23269127 | 3076LOC8100 | | Replace both locomotive fuel vent lines | EFI System | PM02 | 316.14 | 244.22 | 19395340 | 04/04/2013 | 8100 GE-EVO Locomotive |
| 17/02/2014 | 23586415 | 3076LOC8100 | | FMI - Evo fuel mapping software upgrade | EFI System | PM02 | 283.10 | 268.80 | 20924362 | 08/11/2013 | 8100 GE-EVO Locomotive |
| 24/02/2014 | 23623336 | 3076LOC8100 | | Check Evo fuel tank for water ingress | EFI System | PM02 | 141.55 | 135.25 | 21098105 | 02/12/2013 | 8100 GE-EVO Locomotive |
| 10/06/2013 | 23111830 | 3076LOC8100 | | Field Fit Dirty Oil Piping Install Rev 2 | Oil System | PM02 | 1,558.08 | 1,211.26 | 18617530 | 07/12/2012 | 8100 GE-EVO Locomotive |
| 24/02/2014 | 23650066 | 3076LOC8100 | | Evo Loco Dirty Oil Pipe Clamp Re-Fit | Oil System | PM02 | 283.10 | 270.50 | 21221321 | 19/12/2013 | 8100 GE-EVO Locomotive |
| 05/11/2012 | 22951759 | 3076LOC8100 | | EVO Tappet Adjustment & Torque Check | Power Assemblies | PM02 | 498.50 | 249.25 | 17905880 | 07/08/2012 | 8100 GE-EVO Locomotive |
| 22/04/2013 | 22981089 | 3076LOC8100 | | EVO Turbo speed sensor changeout | Sensors | PM02 | 90.01 | 128.59 | 18039961 | 31/08/2012 | 8100 GE-EVO Locomotive |
| 27/08/2012 | 22974837 | 3076LOC8100 | .ECAB | Check Alternator Web Deflections | Bottom End | PM02 | 0.00 | 0.00 | 18009728 | 27/08/2012 | Engine Cab - 15000 |
| 27/08/2012 | 22974982 | 3076LOC8100 | .ECAB | Check Alternator Web Deflections | Bottom End | PM02 | 0.00 | 348.95 | 18010059 | 27/08/2012 | Engine Cab - 15000 |
| 24/06/2013 | 23372303 | 3076LOC8100 | .ECAB | Missing bolt on engine mount. | Bottom End | PM02 | 143.80 | 143.80 | 19887154 | 19/06/2013 | Engine Cab - 15000 |
| 29/04/2013 | 23301150 | 3076LOC8100 | .ECAB | Ob'S Side Air-Air Flange Cracked | Combustion Air System | PM02 | 296.82 | 2,695.27 | 19559471 | 29/04/2013 | Engine Cab - 15000 |
| 24/02/2014 | 23573675 | 3076LOC8100 | .ECAB | ALS Nitrite Level Low Cooling System | Cooling System | PM02 | 141.55 | 135.25 | 20832446 | 31/10/2013 | Engine Cab - 15000 |
| 02/04/2013 | 23269708 | 3076LOC8100 | .ECAB | Fuel Leak from top Filter housing | EFI System | PM02 | 0.00 | 128.59 | 19378223 | 05/04/2013 | Engine Cab - 15000 |
| 04/06/2012 | 22862789 | 3076LOC8100 | .ECAB | Change out Failed Oil Pump Check Valve | Oil System | PM02 | 1,195.92 | 1,061.29 | 17482695 | 23/05/2012 | Engine Cab - 15000 |
| 01/06/2012 | 22871301 | 3076LOC8100 | .ECAB | Change out Failed Oil Pump | Oil System | PM02 | 1,833.75 | 1,208.69 | 17522324 | 31/05/2012 | Engine Cab - 15000 |
| 24/06/2013 | 23372300 | 3076LOC8100 | .ECAB | Oil leak rear of new engine. | Oil System | PM02 | 71.90 | 71.90 | 19887677 | 19/06/2013 | Engine Cab - 15000 |
| 21/10/2013 | 23460621 | 3076LOC8100 | .ECAB | Replace Idler gear cover "O" Rings | Oil System | PM02 | 918.58 | 918.59 | 20333605 | 21/08/2013 | Engine Cab - 15000 |
| 18/05/2012 | 22853288 | 3076LOC8100 | .ECAB | Change out L3 Head - Inspect for Damage | Power Assemblies | PM02 | 10,366.31 | 10,466.00 | 17438846 | 15/05/2012 | Engine Cab - 15000 |
| 24/06/2013 | 23192249 | 3076LOC8100 | .RCAB | check possible radiator leak | Cooling System | PM02 | 143.80 | 143.80 | 19017329 | 10/02/2013 | Radiator Cab - 16000 |
| 05/12/2012 | 23111685 | 3076LOC8101 | | COP inductor boost flange adaptor mod | Bottom End | PM02 | 99.70 | 24.93 | 18617224 | 07/12/2012 | 8101 GE-EVO Locomotive |
| 23/01/2012 | 22613054 | 3076LOC8101 | | Broken turbo lockwire | Combustion Air System | PM02 | 99.70 | 99.70 | 16285690 | 04/10/2011 | 8101 GE-EVO Locomotive |
| 18/05/2012 | 22857093 | 3076LOC8101 | | Check Eductor Boost & Turbo Supply Lines | Combustion Air System | PM02 | 49.85 | 99.70 | 17453846 | 18/05/2012 | 8101 GE-EVO Locomotive |
| 01/07/2013 | 23021493 | 3076LOC8101 | | Turbo Flex Duct Allignment | Combustion Air System | PM02 | 12,412.04 | 12,412.04 | 18200458 | 28/09/2012 | 8101 GE-EVO Locomotive |
| 01/07/2013 | 23267061 | 3076LOC8101 | | EVO 8" Air to Air duct FMI - Upgrade | Combustion Air System | PM02 | 543.36 | 271.68 | 19389386 | 04/04/2013 | 8101 GE-EVO Locomotive |
| 01/07/2013 | 23269128 | 3076LOC8101 | | Replace both locomotive fuel vent lines | EFI System | PM02 | 308.18 | 308.16 | 19395341 | 04/04/2013 | 8101 GE-EVO Locomotive |
| 24/02/2014 | 23586416 | 3076LOC8101 | | FMI - Evo fuel mapping software upgrade | EFI System | PM02 | 283.10 | 0.00 | 20924363 | 08/11/2013 | 8101 GE-EVO Locomotive |
| 03/03/2014 | 23623337 | 3076LOC8101 | | Check Evo fuel tank for water ingress | EFI System | PM02 | 135.25 | 135.25 | 21098107 | 02/12/2013 | 8101 GE-EVO Locomotive |
| 04/03/2013 | 23111831 | 3076LOC8101 | | Field Fit Dirty Oil Piping Install Rev 2 | Oil System | PM02 | 3,423.97 | 3,269.61 | 18617531 | 07/12/2012 | 8101 GE-EVO Locomotive |
| 03/03/2014 | 23650067 | 3076LOC8101 | | Evo Loco Dirty Oil Pipe Clamp Re-Fit | Oil System | PM02 | 270.50 | 270.50 | 21221322 | 19/12/2013 | 8101 GE-EVO Locomotive |
| 15/10/2012 | 22951760 | 3076LOC8101 | | EVO Tappet Adjustment & Torque Check | Power Assemblies | PM02 | 498.50 | 249.25 | 17905881 | 07/08/2012 | 8101 GE-EVO Locomotive |
| 21/10/2013 | 22981139 | 3076LOC8101 | | EVO Turbo speed sensor changeout(Comple | Sensors | PM02 | 106.96 | 0.00 | 18040210 | 31/08/2012 | 8101 GE-EVO Locomotive |
| 27/08/2012 | 22974882 | 3076LOC8101 | .ECAB | Check Alternator Web Deflections | Bottom End | PM02 | 0.00 | 348.95 | 18009916 | 27/08/2012 | Engine Cab - 15000 |
| 28/10/2013 | 23458701 | 3076LOC8101 | .ECAB | Change Out Main Bearing | Bottom End | PM02 | 916.80 | 0.00 | 20326847 | 20/08/2013 | Engine Cab - 15000 |

Figure B.1: Sample of PM02 source data

| Bas. start date | Order | Functional Loc. | | Description | Engine Subsystem | System status | Order Type | TotalPlnndCosts | Total act.costs | Notification | Created on |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11/05/2012 | 32212836 | 3076LOC8100 | .ECAB | Engine shutdown. Rx low oil presure | Oil System | TECO CNF PRT NMAT PRC SETC | PM03 | 0 | 199.4 | 17412313 | 11.05.2012 |
| 4/06/2012 | 32221634 | 3076LOC8100 | .ECAB | Shut Down, Don't Attempt Restart | Oil System | CLSD CNF PRT NMAT PRC SETC | PM03 | 99.7 | 2,043.85 | 17461917 | 22.05.2012 |
| 22/11/2012 | 32377006 | 3076LOC8100 | .ECAB | Fuel Pump CB Tripping | EFI System | REL CNF GMPS MACM PPRT PRC SETC | PM03 | 15,234.70 | 15,633.51 | 18529848 | 22.11.2012 |
| 5/10/2013 | 32688923 | 3076LOC8100 | .ECAB | C Reported Flames Coming From Stack | EFI System | TECO CNF GMPS MACM PPRT PRC SETC | PM03 | 78,173.38 | 5,830.66 | 20634807 | 04.10.2013 |
| 12/07/2012 | 32266664 | 3076LOC8101 | .ECAB | Inspect Fuel Boost Pump | EFI System | REL GMPS MACM PPRT PRC SETC | PM03 | 19,069.62 | 18,920.06 | 17763132 | 18.07.2012 |
| 12/08/2012 | 32285678 | 3076LOC8101 | .ECAB | Investigate engine shutdown.Turbo Sensors | Sensors | REL PCNF CSER GMPS MACM PPRT PRC SETC | PM03 | 748.98 | 948.38 | 17923084 | 10.08.2012 |
| 5/09/2013 | 32663325 | 3076LOC8101 | .ECAB | 8101 Turbo Failure. | Combustion Air System | REL PRT GMPS MACM PRC SETC | PM03 | 104,080.07 | 2,956.85 | 20437740 | 08.09.2013 |
| 16/12/2013 | 32767103 | 3076LOC8101 | .ECAB | COP Fault. | Combustion Air System | REL CNF PRT NMAT PRC SETC | PM03 | 0 | 1,072.40 | 21193230 | 15.12.2013 |
| 25/04/2012 | 32200396 | 3076LOC8102 | .ECAB | Replace flexy duct on air to air | Combustion Air System | TECO CNF GMPS MACM PPRT PRC SETC | PM03 | 6,108.18 | 6,307.58 | 17333868 | 24.04.2012 |
| 11/02/2013 | 32454900 | 3076LOC8102 | .ECAB | Replace fuel boost pump | EFI System | REL PCNF PRT GMPS MACM PRC SETC | PM03 | 8,721.46 | 9,011.10 | 19028885 | 10.02.2013 |
| 20/02/2013 | 32464947 | 3076LOC8102 | .ECAB | Water Pump Failure | Cooling System | TECO CNF GMPS NTUP PPRT PRC SETC | PM03 | 10,039.62 | 8,623.95 | 19093824 | 20.02.2013 |
| 16/10/2013 | 32701357 | 3076LOC8103 | .ECAB | Replace broken turbo bolts | Combustion Air System | REL CNF PRT GMPS MACM PRC SETC | PM03 | 22.38 | 327.98 | 20725621 | 16.10.2013 |
| 22/12/2012 | 32405847 | 3076LOC8104 | | Inspect and ReTighten Turbo Speed Sensors | Combustion Air System | REL CNF PRT NMAT PRC SETC | PM03 | 0 | 99.7 | 18704271 | 22.12.2012 |
| 12/11/2012 | 32367491 | 3076LOC8104 | .ECAB | Replace fuel boost pump | EFI System | REL CNF GMPS MACM PPRT PRC SETC | PM03 | 15,384.25 | 15,384.25 | 18471100 | 12.11.2012 |
| 26/12/2012 | 32408418 | 3076LOC8104 | .ECAB | Investigate flames coming from exhaust | Combustion Air System | TECO CNF PRT NMAT PRC SETC | PM03 | 0 | 149.55 | 18720391 | 25.12.2012 |
| 24/03/2013 | 32498857 | 3076LOC8104 | .ECAB | R3 power assy has fuel leak | Power Assemblies | REL CNF PRT NMAT PRC SETC | PM03 | 0 | 463.14 | 19319975 | 25.03.2013 |
| 7/06/2013 | 32572318 | 3076LOC8104 | .ECAB | Investigate Engine Fault | EFI System | REL CNF GMPS MACM PPRT PRC SETC | PM03 | 7,106.75 | 7,106.75 | 19827994 | 08.06.2013 |
| 9/06/2013 | 32573014 | 3076LOC8104 | .ECAB | Replace R2 Power Assembly | Cooling System | REL GMPS MACM PPRT PRC SETC | PM03 | 28,670.08 | 27,519.68 | 19840991 | 09.06.2013 |
| 12/06/2013 | 32573014 | 3076LOC8104 | .ECAB | Replace R2 Power Assembly | Oil System | REL PCNF GMPS MACM PPRT PRC SETC | PM03 | 28,670.08 | 30,683.27 | 19840991 | 09.06.2013 |
| 20/08/2013 | 32640165 | 3076LOC8104 | .ECAB | Replace Oil cooler | Oil System | TECO CNF GMPS NTUP PPRT PRC SETC | PM03 | 1,668.48 | 556.16 | 20300301 | 16.08.2013 |
| 8/07/2012 | 32258341 | 3076LOC8104 | .ECAB | Change out Failed Water Pump | Cooling System | REL CNF GMPS MACM PPRT PRC SETC | PM03 | 1,229.22 | 1,229.21 | 17739669 | 07.07.2012 |
| 14/01/2014 | 32796827 | 3076LOC8105 | .ECAB | Turbo to Change | Combustion Air System | REL GMPS MSPT PPRT PRC SETC | PM03 | 138,666.11 | 135,546.80 | 21391484 | 14.01.2014 |
| 20/01/2014 | 32796827 | 3076LOC8105 | .ECAB | Turbo to Change | Combustion Air System | TECO CNF GMPS MACM PPRT PRC SETC | PM03 | 138,666.12 | 138,881.97 | 21391484 | 14.01.2014 |
| 11/07/2013 | 32604319 | 3076LOC8105 | /ECAB | Water Leaking From Engine | Cooling System | TECO CNF GMPS MACM PPRT PRC SETC | PM03 | 4,845.42 | 5,660.45 | 20056129 | 10/07/2013 |
| 4/09/2012 | 32305785 | 3076LOC8106 | .ECAB | Change out Failed Turbo Speed Sensors | Sensors | TECO CNF GMPS MACM PPRT PRC SETC | PM03 | 895.01 | 1,094.41 | 18063023 | 04.09.2012 |
| 16/09/2012 | 32316274 | 3076LOC8106 | .ECAB | Engine oil leak Failure | Oil System | TECO CNF GMPS MACM PPRT PRC SETC | PM03 | 470.76 | 570.46 | 18133711 | 16.09.2012 |
| 7/10/2013 | 32691902 | 3076LOC8106 | .ECAB | 8106 01-0069 Fuel Pressure < 30 psig | EFI System | TECO CNF GMPS MACM PPRT PRC SETC | PM03 | 4,041.31 | 4,423.29 | 20645196 | 07.10.2013 |
| 12/10/2012 | 32338914 | 3076LOC8106 | .RCAB | Change out Leaking Companion Sight Glass | Cooling System | REL CNF PRT MACM PRC SETC | PM03 | 263.05 | 598.2 | 18287793 | 12.10.2012 |
| 26/05/2013 | 32559191 | 3076LOC8107 | .ECAB | Investigate Oil Leak | Oil System | TECO CNF PRT NMAT PRC SETC | PM03 | 0 | 133.83 | 19747860 | 26.05.2013 |
| 26/05/2013 | 32559191 | 3076LOC8107 | .ECAB | Investigate Oil Leak | Oil System | REL CNF PRT NMAT PRC SETC | PM03 | 0 | 133.83 | 19747860 | 26/05/2013 |
| 25/06/2012 | 32247250 | 3076LOC8108 | .ECAB | Investigate low water/ lube oil pressure | Power Assemblies | REL CNF GMPS MACM PPRT PRC SETC | PM03 | 19,837.27 | 22,032.85 | 17640560 | 24.06.2012 |
| 2/07/2012 | 32254772 | 3076LOC8108 | .ECAB | Level 3 Shutdown do not Restart | Sensors | REL CNF GMPS MACM PPRT PRC SETC | PM03 | 742.21 | 2,621.41 | 17704981 | 03.07.2012 |
| 5/09/2013 | 32663329 | 3076LOC8108 | .ECAB | 8108 Turbo Failure | Combustion Air System | REL PRT GMPS MACM PRC SETC | PM03 | 104,080.07 | 2,956.85 | 20438026 | 08.09.2013 |
| 29/09/2013 | 32663329 | 3076LOC8108 | .ECAB | 8108 Turbo Failure | Combustion Air System | TECO CNF GMPS MACM PPRT PRC SETC | PM03 | 87,581.41 | 94,073.64 | 20438026 | 08.09.2013 |
| 02/01/2012 | 32108939 | 3076LOC8109 | .ECAB | L3 Power Assembly Destroyed | Power Assemblies | CLSD CNF GMPS NTUP PPRT PRC SETC | PM03 | 13,915.96 | 15,068.14 | 16737250 | 27/12/2011 |
| 27/08/2012 | 32300507 | 3076LOC8109 | .ECAB | Replace Power Assembly. R1 | Power Assemblies | TECO CNF GMPS MACM PPRT PRC SETC | PM03 | 8,871.56 | 9,469.75 | 18011672 | 29.08.2012 |
| 19/04/2013 | 32523092 | 3076LOC8109 | .ECAB | Investigate Oil Leak | Oil System | REL CNF NMAT PPRT PRC SETC | PM03 | 0 | 707.26 | 19485379 | 18/04/2013 |

Figure B.2: Sample of PM03 source data

| Id | Train Id | Primary [ | For Revi | Lead Loc | Loco Ids | Causing | EVO or [ | StartDateTime | Effective | Cause | Effect | Engine Subsystem | Comments | Primary Record Id | Knock Or | KM Peg | Line | Primary Record | Causing Asset |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 569433 | Y0444 | TRUE | | 7057 | 705,781,188,176 | 8118 | EVO | 28/02/2013 1:08 | 15 | Engine S | Fuel System Trouble Other | EFI System | 5054 : Fuel pump problem, loco isolated from coast, workshops known battery knife switch pulled at JD, loco alarm bell ringing from 338-JD. Fuel pressure fault. BR | | FALSE | 362 | YA | | 0 |
| 573127 | M0095 | TRUE | | 8133 | 813,370,609,429 | 8133 | EVO | 3/03/2013 14:22 | 249 | Engine S | Fuel System Leak | EFI System | 15061; After DLC set up driver went back to isolate middle unti and noticed fuel on the running board, driver opened up compartment and saw fuel from the injector spraying out, loco was then shut down and workshops notified. | | FALSE | | | | 0 |
| 652922 | T0194 | TRUE | | 8165 | 816,581,559,432 | 8155 | EVO | 5/03/2013 21:39 | 32 | Engine S | Diesel Engine Not Loading Properly | Combustion Air | #2411 - less then half power from RO - TP. Change MV cable on front of locos after connections appeared to be loose. Power ok now. | | FALSE | 293 | TP | | 0 |
| 671746 | Y0467 | TRUE | | 7065 | 706,581,357,097 | 8135 | EVO | 6/03/2013 6:33 | 10 | Engine S | Diesel Engine Crankcase Overpressure | Unknown | 16254- crankcase overpressure, loco isolated. | | FALSE | 411 | YA | | 0 |
| 688361 | H0310 | TRUE | | 7094 | 709,481,208,101 | 8120 | EVO | 7/03/2013 11:05 | 25 | Engine S | Diesel Engine Not Loading Properly | Unknown | #7766 - middle unit 8120 lost power @ HJ, message read loco needs repairs, loco wont load properly. Arranged for HD bankers to assist - to be attached @ SP | | FALSE | 411 | LHR | | 0 |
| 688607 | H0310 | TRUE | | 7094 | 709,481,208,101 | 8120 | EVO | 7/03/2013 12:05 | 25 | Engine S | Diesel Engine Not Loading Properly | Unknown | #7766 - middle unit 8120 lost power @ HJ, message read loco needs repairs, loco wont load properly. Arranged for HD bankers to assist - bankers being re-attached @ SP | | FALSE | 385 | WA | | 0 |
| 692455 | W0279 | TRUE | | 9432 | 943,281,558,165 | 8155 | EVO | 8/03/2013 2:46 | 10 | Engine S | Diesel Engine Loss Of Power | Cooling System | 1572; Middle unit derating more than 20% due to hot pre-turbine temperature, W/Shops advised, told to run offline | | FALSE | 62 | TP | | 0 |
| 695385 | Y0477 | TRUE | | 8114 | 811,481,748,148 | 8114 | EVO | 8/03/2013 16:16 | 25 | Engine S | Fuel System Trouble Other | EFI System | 2231; 2227 and 2230 (Not fault forms for this fault but both faults on same loco and same train) Loco Fault 8114 shutdown, talked to workshops | | FALSE | 73 | WC | | 0 |
| 699475 | H0318 | TRUE | | 8116 | 811,681,807,092 | 8116 | EVO | 9/03/2013 7:39 | 11 | Engine S | Diesel Engine Power Assembly Trouble | Power Assembly | 7033; Observed oil on running board, checked loco and found cylinder head bolts loose and oil leaking workshops notified, loco shut down | | FALSE | 210 | TP EML | | 0 |
| 701564 | H0318 | TRUE | TRUE | 8116 | 811,681,807,092 | 8116 | EVO | 9/03/2013 19:03 | 116 | Engine S | Diesel Engine will not start or Run | Unknown | 16551 : shunt 3 locos from empty HD to loaded HD due to lead loco being dead unit, fully isolated. | | FALSE | 460 | LHR | | 0 |
| 709030 | P0223 | TRUE | | 7061 | 706,181,328,123 | 8123 | EVO | 11/03/2013 1:43 | 20 | Engine S | Diesel Engine will not start or Run | Power Assembly | No Fault Form - Stopped 69km loco fault, rear loco shut | | FALSE | 64 | TP | | 0 |
| 712669 | P0223 | TRUE | TRUE | 7061 | 706,194,348,123 | 8123 | EVO | 11/03/2013 19:33 | 3 | Engine S | Diesel Engine Crankcase Overpressure | Unknown | No Fault Form - Loco shut down only 2 working locos - slow running between PA & WJ. Loco 8123 shutdown with a COP | | FALSE | 318 | PA | | 0 |
| 718370 | W0297 | TRUE | | 8159 | 815,981,487,047 | 8159 | EVO | 13/03/2013 10:13 | 86 | Cooling | Cooling System Trouble Other | Cooling System | 3657 : Loco required coolant, shunted to service road - 13/03/2013 - 10:30 | | FALSE | 13 | WA | | 0 |
| 719136 | W0299 | FALSE | | 9431 | 943,181,818,169 | | EVO | 13/03/2013 14:22 | 177 | Cooling | Cooling System Trouble Other | Cooling System | 5615 : Low water, only enough to idle, retention tank full, engine oil on low, train banked out of WA to Hawk - 13/03/2013 - 16:30 | [Tag 10] - [W0298] - [Depart Train From Loc | TRUE | 423 | WA | 719876 | 8115 |
| 719876 | W0298 | TRUE | | 8115 | 811,594,308,130 | 8115 | EVO | 13/03/2013 16:30 | 258 | Cooling | Cooling System Trouble Other | Cooling System | 5615 : Low water, only enough to idle, retention tank full, engine oil on low, train banked out of WA to Hawk - 13/03/2013 - 16:30 | | FALSE | 419 | WA | | 0 |
| 722177 | H0334 | TRUE | | 8131 | 813,181,767,057 | 8131 | EVO | 14/03/2013 2:01 | 154 | Engine S | Diesel Engine Sensor Trouble | Sensor | 05160- failure in crank sensor 1 and 2- loco oculd not be lifted, had to wait for 0700 sign on to bank train. | | FALSE | 262 | LHR | | 0 |
| 724630 | H0334 | TRUE | | 8131 | 813,181,767,057 | 8131 | EVO | 14/03/2013 4:36 | 83 | Engine S | Diesel Engine Sensor Trouble | Sensor | 05160- failure in crank sensor 1 and 2- loco oculd not be lifted, had to wait for 0700 sign on to bank train. | | FALSE | | | | 0 |
| 724641 | H0334 | TRUE | | 8131 | 813,181,767,057 | 8131 | EVO | 14/03/2013 5:59 | 158 | Engine S | Diesel Engine Sensor Trouble | Sensor | 05160- failure in crank sensor 1 and 2- loco oculd not be lifted, had to wait for 0700 sign on to bank train. | | FALSE | | | | 0 |
| 727684 | B0027 | TRUE | | 9409 | 940,981,567,074 | 8156 | EVO | 15/03/2013 8:15 | 35 | Engine S | Lubrication System Oil Leak | Oil System | #7719 - Unit alarm on 8156, went back to inspect unit, and discovered oil all over unit. Contacted workshops. Deemed total failure. | | FALSE | 257 | Unknown Line | | 0 |
| 759455 | Y0554 | TRUE | TRUE | 8161 | 816,170,828,116 | 8116 | EVO | 21/03/2013 18:40 | 9 | Cooling | Cooling System Trouble Other | Cooling System | No Loco Fault Form : 3rd loco offline (low water, etc) - 410.9KM 21/03/2013 - 18:35 | | FALSE | 429 | YA | | 0 |
| 759503 | Y0555 | FALSE | TRUE | 7057 | 705,781,768,150 | | EVO | 21/03/2013 18:00 | 35 | Cooling | Cooling System Trouble Other | Cooling System | No Loco Fault Form : 3rd loco offline (low water, etc) - 410.9KM 21/03/2013 - 18:35 | [Tag 22] - [Y0554] - [Mine to Rosella] - [759 | TRUE | 446 | YA | 759455 | 8116 |
| 779620 | P0256 | TRUE | | 8155 | 8,155,816,581,648,120 | 8125 | EVO | 25/03/2013 12:56 | 24 | Engine S | Lubrication System Oil Leak | Oil System | No Fault Form - Banker loco leaking oil, 939 fixed | | FALSE | 386 | WC | | 0 |
| | | | | | | | | | | | | | 10802 : Continuing power problems, previous bookings, previously ran offline, problem still exists, derating, only just | | | | | | |

Figure B.3: Sample of Network Delay source data

| Column1 | Incident Date | Engine System | Special Cause? | Fleet | Incident Status | Lead Investigator | Operating Responsibility | Work Area (Site Location) | Impact Type | Actual Consequence | Consequence Rating | Maximum Reasonable Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Empty train oil spill Yandi line 351KM | 03.04.2012 | Oil System | Dirty Oil Pipe Victaulic | EVO | Closed | Laurence Healey | Rolling Stock Maintenance Locos | 2RI Finch - Hawk line | Environment Impact | 1-Minor | 1 | Moderate |
| Fuel spill from Locomotive 8150 | 25.04.2012 | EFI System | | EVO | Closed | Sumesh Duvvuru | Rolling Stock Maintenance Locos | 2RI Rosella - Yandicoogina line | Environment | 2-Medium | 2 | Moderate |
| Oil spill from Loco 8131 at Lizard. | 10.05.2012 | Oil System | Dirty Oil Pipe Victaulic | EVO | Closed | Laurence Healey | Locomotive Maintenance A | 2RI Dampier - Tom Price line | Environment Impact | 2-Medium | 2 | Moderate |
| 8124 engine failure at West Ang rail loop | 03.08.2012 | Power Assemblies | Piston Failures | EVO | Closed | Laurence Healey | Rolling Stock Maintenance Locos | 2RI Juna Downs - West Angelas line | Environment Impact | 1-Minor | 1 | Low |
| Loco experienced crankcase over pressure causing oil spill | 15.08.2012 | Power Assemblies | | EVO | Closed | Laurence Healey | Rolling Stock Maintenance Locos | 2RI Banksia - Mallee line | Environment Impact | 1-Minor | 1 | Low |
| Oil leak in Yandi yard from loco 8140 | 27.08.2012 | Power Assemblies | Dirty Oil Pipe Victaulic | EVO | Closed | Laurence Healey | Rolling Stock Maintenance Locos | 2RI Yandicoogina yard | Environment Impact | 1-Minor | 1 | Moderate |
| Loco had a oil leak coming out of Hope Downs | 28.11.2012 | Oil System | Dirty Oil Pipe Victaulic | EVO | Closed | Brett Hunter | Locomotive Maintenance A | 2RI Railway lines | Environment Impact | 1-Minor | 1 | Low |
| Locomotive 8144 engine bay fire | 19.12.2012 | EFI System | | EVO | Closed | Laurence Healey | Rolling Stock Maintenance Locos | 2RI Teal siding | Environment | 2-Medium | 2 | Moderate |
| Maintainer covered in sump oil. | 13.01.2013 | Oil System | | EVO | Closed | Brett Hunter | Locomotive Maintenance A | 2RI Rolling stock maintenance | Safety Impact | 1-Minor | 1 | Low |
| Locomotive loses oil and shuts down on Yandi mainline | 15.01.2013 | Oil System | Dirty Oil Pipe Victaulic | EVO | Closed | Shaun Pikor | Rolling Stock Maintenance Locos | 2RI Osprey - Quail line | Environment Impact | 1-Minor | 1 | Moderate |
| Diesel fuel leak from loco 8133 engine | 04.03.2013 | EFI System | | EVO | Closed | Shaun Pikor | Locomotive Maintenance B | 2RI Rosella - Yandicoogina line | Environment | 0-Near Miss or Near | 0 | Low |
| Small fire from Turbo failure. | 05.09.2013 | Combustion Air | | EVO | Conference | Brett Hunter | Rolling Stock Maintenance Locos | 2RI Rosella - Brockman line | Process Impact | 1-Minor | 1 | Low |
| 8122 oil leak. | 01.02.2014 | Oil System | Dirty Oil Pipe Victaulic | EVO | In Process | Shaun Pikor | Rolling Stock Maintenance Locos | 2RI Brolga - Dingo line | Environment Impact | 1-Minor | 1 | Low |
| Locomotive 8117 had external oil leak, retention tank spill | 13.02.2014 | Oil System | Dirty Oil Pipe Victaulic | EVO | In Process | Chris Stewart | Locomotive Maintenance C | 2RI 7 Mile load box | Environment Impact | 1-Minor | 1 | Low |

Figure B.4: Sample of HSE Incident source data

# Appendix C

# Subsystem Boundary Definitions

## C.1 Engine Subsystem Boundary Definitions

Appendix C contains the Boundary Definitions for the analysed subsystems.

## RCM – Systems Analysis

| | | | |
|---|---|---|---|
| **Step 2-1:** | System Boundary Definition | **Revision:** | 0 |
| **Information:** | Boundary Overview | **Date:** | 30 March 2014 |
| **Plant:** | GE Evolution Locomotive | | |
| **System:** | Engine System | | |
| **Subsystem:** | Fuel System | | |
| **Analyst(s):** | Caleb Mayne (Facilitator) | | |

**Major Equipment Included:**

- Fuel Injector
- Fuel Transfer Pump
- High Pressure Fuel Pump, pushrod and crosshead
- Piping, low pressure and high pressure
- Fuel filters
- Return fuel pressure regulator

**Primary Physical Boundaries:**

**Start with:**

- Fuel entering fuel transfer pump suction port
- Mechanical power input to the crosshead/pushrod from camshaft

**Terminate with:**

- Fuel leaving the return fuel pressure regulator
- Fuel entering combustion cylinder from injector nozzle

**Caveats:**

-

Figure C.1: Fuel System Boundary Overview

## RCM – Systems Analysis

| | | | |
|---|---|---|---|
| **Step 2-2:** | System Boundary Definition | **Revision:** | 0 |
| **Information:** | Boundary Details | **Date:** | 30 March 2014 |
| **Plant:** | GE Evolution Locomotive | | |
| **System:** | Engine System | | |
| **Subsystem:** | Fuel System | | |
| **Analyst(s):** | Caleb Mayne (Facilitator) | | |

| **Type** | **Bounding System** | **Interface location** | **Drawing/Schematic reference** |
|---|---|---|---|
| In | Fuel suction piping (not included) | Fuel transfer pump suction port | |
| Out | Power Assemblies – Combustion chamber | Injector nozzle | |
| In | Bottom End – Camshaft fuel pump lobe | Crosshead roller | |
| Out | Fuel return piping (not included) | Discharge of Return fuel pressure regulator | |

Figure C.2: Fuel System Boundary Details

## RCM – Systems Analysis

| | | | |
|---|---|---|---|
| **Step 2-1:** | System Boundary Definition | **Revision:** | 0 |
| **Information:** | Boundary Overview | **Date:** | 17 June 2014 |
| **Plant:** | GE Evolution Locomotive | | |
| **System:** | Engine System | | |
| **Subsystem:** | Power Assemblies | | |
| **Analyst(s):** | Caleb Mayne (Facilitator) | | |

**Major Equipment Included:**

- Cylinder liner
- Piston
- Connecting Rod
- Strongback
- Head
- Push Rods & Cross heads
- Valves & rocker gear
- Studs

**Primary Physical Boundaries:**

**Start with:**

- Gasket between the strong back and mainframe
- Crosshead rollers receiving mechanical power input
- Atomised fuel leaving the injector (fuel system excluded)

**Terminate with:**

- Mechanical power output to the crankshaft

**Caveats:**

-

Figure C.3: Power Assemblies Boundary Overview

## RCM – Systems Analysis

**Step 2-2:** System Boundary Definition  **Revision:** 0

**Information:** Boundary Details  **Date:** 17 June 2014

**Plant:** GE Evolution Locomotive

**System:** Engine System

**Subsystem:** Power Assemblies

**Analyst(s):** Caleb Mayne (Facilitator)

| Type | Bounding System | Interface location | Drawing/Schematic reference |
|---|---|---|---|
| In | Bottom End | Gasket between strong back and mainframe | |
| In | Bottom End – Camshaft valve lobes | Crosshead roller | |
| In | Fuel System | Discharge of atomised fuel from the injector | |
| Out | Bottom End | Con rod bearing and crankshaft | |

Figure C.4: Power Assemblies Boundary Details

## RCM – Systems Analysis

| | | | |
|---|---|---|---|
| **Step 2-1:** | System Boundary Definition | **Revision:** | 0 |
| **Information:** | Boundary Overview | **Date:** | 15 August 2014 |
| **Plant:** | GE Evolution Locomotive | | |
| **System:** | Engine System | | |
| **Subsystem:** | Combustion Air | | |
| **Analyst(s):** | Caleb Mayne (Facilitator) | | |

**Major Equipment Included:**

- Spin filters,
- Baggy air filters,
- Turbocharger,
- Water based intercooler,
- Air based intercooler package,
- Seals and pipes.

**Primary Physical Boundaries:**

**Start with:**

- Fresh charge air entering the spin filters,
- Combustion gasses entering the turbocharger,

**Terminate with:**

- Fresh charge air entering the power assembly,
- Combustion gasses leaving the turbocharger,

**Caveats:**

- Cooling water, and secondary damage caused by poor quality cooling water, is not considered in this subsystem.
- Lubricating oil, and secondary damage caused by poor lubrication, is not considered in this subsystem.

Figure C.5: Combustion Air System Boundary Overview

## RCM – Systems Analysis

| | | | |
|---|---|---|---|
| **Step 2-2:** | System Boundary Definition | **Revision:** | 0 |
| **Information:** | Boundary Details | **Date:** | 15 August 2014 |
| **Plant:** | GE Evolution Locomotive | | |
| **System:** | Engine System | | |
| **Subsystem:** | Combustion Air | | |
| **Analyst(s):** | Caleb Mayne (Facilitator) | | |

| **Type** | **Bounding System** | **Interface location** | **Drawing/Schematic reference** |
|---|---|---|---|
| In | Atmosphere | Spin filters | |
| In | Lubricating oil system | Turbocharger oil feed port | |
| In | Exhaust air | Turbocharger inlet flange | |
| Out | Lubricating oil system | Turbocharger oil drain port | |
| Out | Power assemblies | Power assembly air intake port | |
| Out | Exhaust air | Turbocharger to muffler flange | |

Figure C.6: Combustion Air System Boundary Details

# Appendix D

# Bill Of Materials and assembly drawing extract

Figures D.1 and D.2 are extracted from the GE Renewal Parts Catalogue, document PB-16610-010 (GE Transportation 2014). Figure D.3 is extracted from the RTIO maintenance system.

| Item No | Part No | Description | Qty | Tag |
|---|---|---|---|---|
| 1 | 84C626554G1 | FUEL FILTER CANISTER ASSEMBLY | 1 | |
| 1A | 84A212981P3 | FUEL FILTER CANISTER | 2 | |
| 2 | 132X1903 | FUEL FILTER ELEMENT, 2 PIECE, 2 STAGE | 2 | |
| 9 | 84B518778ADG1 | FUEL DRAIN VALVE | 1 | |
| | | | | |
| 1 | 84C626554G1 | FUEL FILTER CANISTER ASSEMBLY | 1 | |
| 1A | 84A212981P3 | FUEL FILTER CANISTER | 2 | |
| 1B | 115X2744 | O-RING, VITON | AR | |
| 1C | 132X1654 | CLAMP, RING | AR | |
| 2 | 132X1903 | FUEL FILTER ELEMENT, 2 PIECE, 2 STAGE | 2 | |
| 3 | N14P35044B13 | BOLT, HEX HD, 3/4 IN-10, 2.75 IN LONG, GRADE 8 | 6 | |
| 4 | 41B537660P16 | WASHER, FLAT, 0.850 IN ID, 1.375 IN OD | 6 | |
| 5 | N405P43B13 | LOCKWASHER, 3/8 IN | 4 | |
| 6 | 84A214768P32 | HOSE ASSEMBLY, 43.83 IN LONG | 1 | |
| 7 | 84A214768P77 | HOSE ASSEMBLY, 73.70 IN LONG | 1 | |
| 8 | 41B541600BFP3 | FITTING, 0.75 IN OD TUBE, 1.3125-12 TO 1.0625-12 | 1 | |
| 9 | 84B518778ADG1 | FUEL DRAIN VALVE | 1 | |
| 10 | 84A214216P1 | FITTING, ELBOW | 2 | |
| 11 | 709808P2 | CLAMP, 0.75 IN | 4 | |
| 12 | N22P25020B13 | BOLT, HEX HD, 3/8 IN-16, 1 1/4 IN LONG | 4 | |
| 13 | 155B9004ABP16 | PIPE, 2.00 IN LONG | 1 | |
| 14 | 41A302321ADP1 | HOSE, 3 PLY, 1.00 IN ID | AR | F |
| 15 | 499A910AAP2 | HOSE CLAMP, 3/4 IN TO 1 3/4 IN | 1 | |
| 16 | 84B518760ABP1 | HOSE ASSEMBLY, 70.00 IN LONG | 1 | |
| 17 | 41A200217P2 | ADAPTER | 2 | |
| 18 | 84A214768P64 | HOSE ASSEMBLY, 63.00 IN LONG | 1 | |
| 19 | 84B518760ABP6 | HOSE ASSEMBLY, 169.64 IN LONG | 1 | |
| 20 | 41B542608EVP1 | HOSE ASSEMBLY, 1.00 NOM, 61.60 IN LONG | 1 | |
| 21 | 41B541600ACP28 | ADAPTER, 1 IN MPT, 1 5/16 IN-12 MPT, 1.00 IN OD TUBE | 1 | |
| 22 | 499A904CYP17 | BUSHING, REDUCING, 2 IN, 1 IN | 1 | |

Figure D.1: Renewal Parts Catalogue Part A - Partial Fuel System Bill Of Materials (GE Transportation 2014)

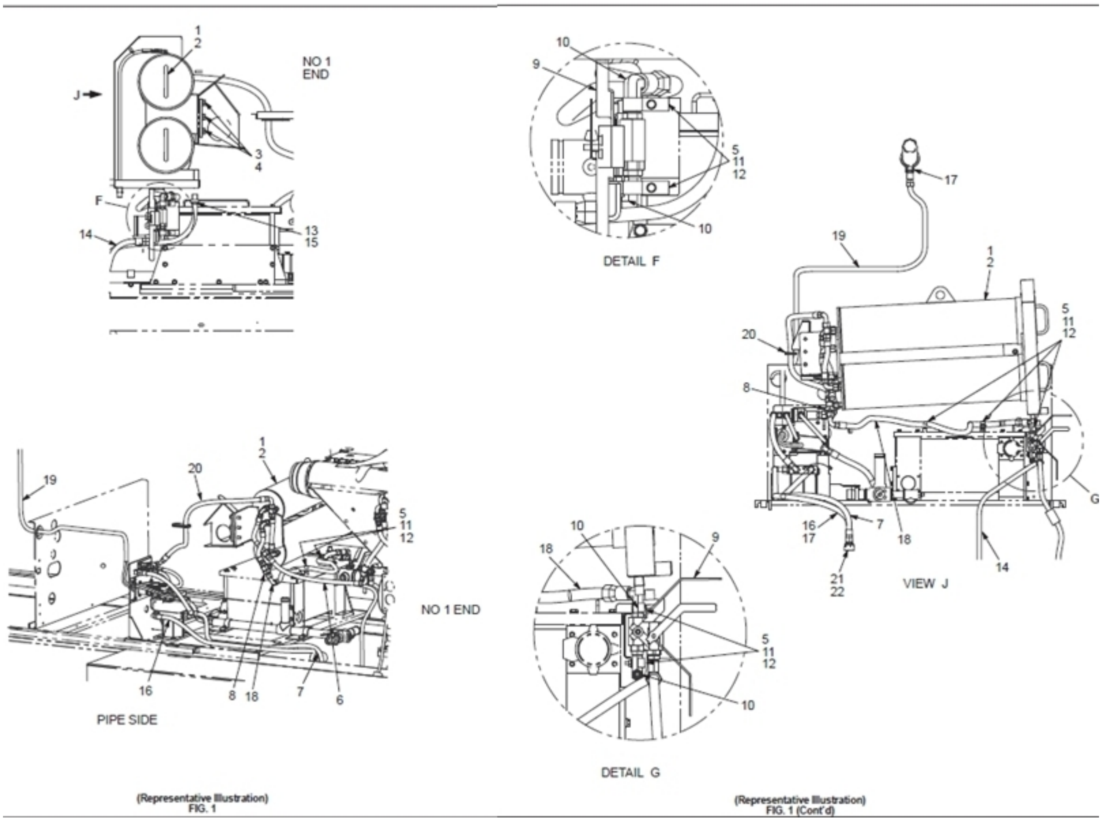


Figure D.2: Renewal Parts Catalogue Part B - Partial Fuel System Assembly Drawing (GE Transportation 2014)

| | | | | | |
|---|---|---|---|---|---|
| \|-- | 60106007 | GE-EVO Fuel System | I | 1.000 | EA |
| \|--- | 20254517 | ADAPTER;GEC;240X1067 | L | 1.000 | EA |
| \|--- | 20182571 | BLOCK;PUMP;FUEL;340X1009 | L | 1.000 | EA |
| \|--- | 20254555 | BOLT;BANJO;GEC;215X1099 | L | 1.000 | EA |
| \|--- | 20011357 | CLAMP;FUEL INJECTOR;GE 223X1002 | L | 1.000 | EA |
| \|--- | 20254601 | CLAMP;GEC;214X1020 | L | 1.000 | EA |
| \|--- | 20254636 | FITTING,HOSE;TURBO;GEC;140X2897 | L | 1.000 | EA |
| \|--- | 20254635 | FITTING;GEC;140X2378 | L | 1.000 | EA |
| \|--- | 20254631 | FITTING;GEC;140X3161 | L | 1.000 | EA |
| \|--- | 20254640 | FLANGE;1" FTP;GEC;140X2845 | L | 1.000 | EA |
| \|--- | 20126010 | FUEL BRACKET ASSY;340X1047-1 | L | 1 | AY |
| \|--- | 20011366 | FUEL LINE;HP KIT;TIER 2;350X1029 | L | 1.000 | KIT |
| \|--- | 20095910 | GASKET;FUEL LEVEL SENSOR,41A314360ABP1 | L | 1.000 | EA |
| \|--- | 20011364 | HOSE ASSEMBLY;84B518760ABP1 | L | 1.000 | EA |
| \|--- | 20011367 | HOSE,FUEL;ASM;GE 84A214768P32 | L | 1.000 | EA |
| \|--- | 20011351 | HOSE,FUEL;FITTED;0.5INX13.5IN LG; | L | 1.000 | EA |
| \|--- | 20011347 | HOSE,FUEL;FITTED;0.5INX19.30IN LG; | L | 1.000 | EA |
| \|--- | 20011369 | HOSE,FUEL;FITTED;25.4MM;45DEG;340X1021-2 | L | 1.000 | EA |
| \|--- | 20011375 | HOSE,FUEL;FITTED;25.4MM;45DEG;340X1022-2 | L | 1.000 | EA |
| \|--- | 20011368 | HOSE,FUEL;FITTED;25.4MM;45DEG;340X1033-2 | L | 1.000 | EA |
| \|--- | 20011381 | HOSE,FUEL;FITTED;25.4MM;45DEG;340X1040-1 | L | 1.000 | EA |
| \|--- | 20011376 | HOSE,FUEL;FITTED;25.4MM;90DEG;340X1020-2 | L | 1.000 | EA |
| \|--- | 20011382 | HOSE,FUEL;FITTED;25.4MM;90DEG;340X1037-1 | L | 1.000 | EA |
| \|--- | 20011374 | HOSE,FUEL;FITTED;25.4MM;90DEG;340X1038-1 | L | 1.000 | EA |
| \|--- | 20011379 | HOSE,FUEL;FITTED;25.4MM;GE 340X1016-3 | L | 1.000 | EA |
| \|--- | 20011377 | HOSE,FUEL;FITTED;25.4MM;GE 340X1042 | L | 1.000 | EA |
| \|--- | 20011360 | HOSE,FUEL;FITTED;403.33MM;GE 340X1017-2 | L | 1.000 | EA |
| \|--- | 20011362 | HOSE,FUEL;FITTED;501.91MM;GE 340X1031-2 | L | 1.000 | EA |
| \|--- | 20011363 | HOSE,FUEL;FITTED;643.88MM;GE 340X1035-1 | L | 1.000 | EA |
| \|--- | 20011371 | HOSE;ASM CNSTR;2 AMT VLV;GE 84A214768P77 | L | 1.000 | EA |
| \|--- | 20011354 | HOSE;FITTED;16IN LG;GE 84B511537ACP2 | L | 1.000 | EA |
| \|--- | 20011352 | HOSE;FITTED;30IN LG;GE 340X1002 | L | 1.000 | EA |
| \|--- | 20011356 | HOSE;FITTED;46.50IN LG;GE 84B511537ACP1 | L | 1.000 | EA |
| \|--- | 20011372 | HOSE;FITTED;GE 341X1007 | L | 1.000 | EA |
| \|--- | 20011370 | HOSE;FUEL FILTER;ASM;GE 84A214768P64 | L | 1.000 | EA |
| \|--- | 20011412 | INJECTOR,FUEL;323X1003-1 | L | 1.000 | EA |
| \|--- | 20011405 | INSTALL ASSEMBLY;INJECTOR;T2;350X1028 | L | 1.000 | KIT |
| \|--- | 20011408 | LINE;FUEL;HP;232X1021-2 | L | 1.000 | EA |
| \|--- | 20095796 | O-RING;1/2" ID,315X1035 | L | 1.000 | EA |
| \|--- | 20106113 | O-RING;GE 215X1015 | L | 1.000 | EA |
| \|--- | 20106125 | O-RING;GEC;232X1002 | L | 1.000 | EA |
| \|--- | 20106126 | O-RING;GE 315X1035 | L | 4.000 | EA |
| \|--- | 20106093 | O-RING;HP FUEL LINE,GE 215X1111 | L | 1.000 | EA |
| \|--- | 20050535 | O-RING;INJECTOR SLVE;GE 221X1039;GP93466 | L | 1.000 | EA |
| \|--- | 20254719 | PIPE;GEC;140X2959 | L | 1.000 | EA |
| \|--- | 20095904 | PLUG ASSY;218X1012 | L | 1.000 | EA |
| \|--- | 20011462 | PUMP,FUEL BOOST;84A215237P1 | L | 1.000 | EA |
| \|--- | 20011435 | PUMP,FUEL;HP;332X1001-1 | L | 1.000 | EA |
| \|--- | 20178903 | SCREW;L115P21050 | L | 1.000 | EA |
| \|--- | 20050538 | SEAL KIT;INJECTOR;GE 250X1008 | L | 1.000 | KIT |
| \|--- | 20050537 | SEAL;INJECTOR SLVE;GE 215X1010;GP93464 | L | 1.000 | EA |
| \|--- | 20106097 | SENSOR,TEMPRATURE;GE 41A296328AAP12 | L | 1.000 | EA |
| \|--- | 20050536 | SLEEVE;INJECTOR;GE 323X1004;GP99801 | L | 1.000 | EA |
| \|--- | 20106118 | STRAINER WITH SEAL;GE 332X1018 | L | 1.000 | EA |
| \|--- | 20095791 | TEST FITTING;340X1028 | L | 1.000 | EA |
| \|--- | 20011407 | VALVE,RELIEF;REG;GE 332X1010 | L | 1.000 | EA |

Figure D.3: RTIO Fuel System Bill Of Materials (BOM)

| Item | Part No. | Description | Qty |
|---|---|---|---|
| 2 | 321X1048 | CYLINDER HEAD ASSEMBLY (INCLUDES 350X1002 AND 350X1003) | 1 |
| 2A | 350X1002 | TIER 2 HEAD CHANGEOUT KIT | 1 |
| 2B | 321X1034 | CYLINDER HEAD ASSEMBLY | 1 |
| 2C | 321X1079 | CYLINDER HEAD ASSEMBLY WITHOUT FUEL SYSTEM COMPONENTS | 1 |
| 3 | 321X1037 | CYLINDER HEAD WITH GUIDES | 1 |
| 25 | 321X1011-2 | BRACKET, ROCKER ARM | 1 |
| 31 | 321X1058 | COVER, CYLINDER HEAD | 1 |
| 32 | 221X1077 | GASKET, CYLINDER HEAD COVER | 1 |
| 33 | 315X1028 | BOLT, FLANGE HEAD, M12 X 1.75, 80 MM LONG | 1 |
| 34 | 115X1021-1 | WASHER, SEAL, 1/2 IN | 1 |
| 35 | 321X1053-3 | COMPRESSION RELIEF VALVE ASSEMBLY | 1 |
| 37 | 321X1040 | SEALING WASHER | 1 |
| 37A | 247X1002 | SEALER, LOCTITE 222 | AR |
| 39 | 321X1035 | HEAD GASKET, CYLINDER | 1 |
| 40 | 321X1005-1 | GASKET, CYLINDER HEAD TO STRONGBACK | 1 |
| 41 | L15P19050 | BOLT, HEX SOC HD, M10 X 1.5, 50 MM LONG | 4 |
| 42 | 321X1049-1 | CYLINDER STRONGBACK ASSEMBLY (INCLUDES ALL OF 321X1045-1 OR 321X1069 AND 350X1086) | 1 |

Figure D.4: Renewal Parts Catalogue Part D - Partial Power Assembly System Bill Of Materials (GE Transportation 2014)

| | | | | | |
|---|---|---|---|---|---|
| \|-- | 60106043 | GE-EVO Power Assembly | I | 1.000 | EA |
| \|-- | 20403489 | BEARING ROD KIT;UPPER&LOWER;GEC;350X1006 | L | 1.000 | EA |
| \|--- | 20095795 | CON ROD;LOWER BEARING SHELL,317X1001 | L | 1.000 | EA |
| \|--- | 20095794 | CON ROD;UPPER BEARING SHELL,317X1007 | L | 1.000 | EA |
| \|--- | 20254552 | BOLT,HEX;M8 X 1.25;40MM LG;GEC;315X1040 | L | 1.000 | EA |
| \|--- | 20254550 | BOLT;FLANGE HEAD;M12 X 1.75;25MM LG | L | 1.000 | EA |
| \|--- | 20254548 | BOLT;FLANGE HEAD;M16 X 2;110MM LG | L | 1.000 | EA |
| \|--- | 20254551 | BOLT;FLANGE HEAD;M16 X 2;40MM LG | L | 1.000 | EA |
| \|--- | 20146410 | BOLT;M12 X 1.75 X 60MM LG;GEC;L115P21060 | L | 1.000 | EA |
| \|--- | 20254549 | BOLT;ROCKER SHAFT;M20 X 2.5;200MM LG | L | 1.000 | EA |
| \|--- | 20254571 | BRACKET;GEC;315X1033 | L | 1.000 | EA |
| \|--- | 20254572 | BRACKET;GEC;315X1041 | L | 1.000 | EA |
| \|--- | 20011344 | CAP,GUARD;CYL STUD;GE 221X1038-1 | L | 1.000 | EA |
| \|--- | 20146404 | CLAMP;EXHAUST;GEC;228X1004-1 | L | 1.000 | EA |
| \|--- | 20254785 | CONE,HALF;VALVE;GEC;221X1024 | L | 1.000 | EA |
| \|--- | 20146399 | EXHAUST;GEC;328X1025 | L | 1.000 | EA |
| \|--- | 20011398 | GASKET KIT;CYL HEAD;GE 350X1003 | L | 1.000 | KIT |
| \|--- | 20106105 | GASKET;GE 321X1005 | L | 1.000 | EA |
| \|--- | 20106104 | GASKET;GE 321X1035 | L | 1.000 | EA |
| \|--- | 20146401 | GASKET;GEC;126X1809 | L | 1.000 | EA |
| \|--- | 20011358 | GASKET;HEAD;CYLINDER;84E930252P1 | L | 1.000 | EA |
| \|--- | 20095804 | GASKET;ROCKER COVER;221X1077 | L | 1.000 | EA |
| \|--- | 20095798 | GASKET;STRONG BACK TO TOPDECK,315X1000-2 | L | 1.000 | EA |
| \|--- | 20011487 | HEAD,ENGINE;GE 321X1034 | L | 1.000 | EA |
| \|--- | 20106110 | KIT;GE 350X1004 | L | 1.000 | EA |
| \|--- | 20095792 | NUT,STRETCH;M36X2,321X1059 | L | 4.000 | EA |
| \|--- | 20106109 | O-RING;321X1002 | L | 1.000 | EA |
| \|--- | 20095806 | O-RING;50MM ID,VITON,215X1016 | L | 1.000 | EA |
| \|--- | 20106113 | O-RING;GE 215X1015 | L | 1.000 | EA |
| \|--- | 20106139 | O-RING;GE 239X1013 | L | 1.000 | EA |
| \|--- | 20106108 | O-RING;GE 321X1024 | L | 1.000 | EA |
| \|--- | 20106130 | O-RING;GE 41A219499P230 | L | 1.000 | EA |
| \|--- | 20106107 | O-RING;GE;321X1001-2 | L | 1.000 | EA |
| \|--- | 20146402 | O-RING;GEC;221X1019 | L | 1.000 | EA |
| \|--- | 20254721 | PISTON & ROD ASSY;GEC;322X1027 | L | 1.000 | EA |
| \|--- | 20011461 | PISTON AND CONROD ASSY;322X1006-1 | L | 1.000 | EA |
| \|--- | 20254772 | PLUG;SOCKET HEAD;THREADED;GEC;215X1007 | L | 1.000 | EA |
| \|--- | 20254773 | PLUG;SOCKET HEAD;THREADED;GEC;215X1009 | L | 1.000 | EA |
| \|--- | 20011474 | POWER ASSY;UPPER;322X1007 | L | 1.000 | EA |
| \|--- | 20254776 | RETAINER,SPRING;GEC;321X1021-1 | L | 1.000 | EA |
| \|--- | 20011402 | RING KIT;PISTON;350X1005 | L | 1.000 | KIT |
| \|--- | 20106098 | RING,PISTON RETAINING;GE 342X1016 | L | 2.000 | EA |
| \|--- | 20254756 | RING,SEALING;A12X15.5 CU;GEC;215X1030 | L | 1.000 | EA |
| \|--- | 20106106 | RING;GE 321X1047-1 | L | 1.000 | EA |
| \|--- | 20095793 | ROCKER COVER;321X1058 | L | 1.000 | EA |
| \|--- | 20011340 | SEAL,O-RING;CYL STUD;GE 215X1000 | L | 1.000 | EA |
| \|--- | 20011346 | SEAL,O-RING;GE 41A219499ABP246 | L | 1.000 | EA |
| \|--- | 20011341 | SEAL,O-RING;VITON 4;GE 215X1106 | L | 1.000 | EA |
| \|--- | 20011342 | SEAL,O-RING;VITON 4;GE 215X1107 | L | 1.000 | EA |
| \|--- | 20146408 | SPACER;GEC;115X2594 | L | 1.000 | EA |
| \|--- | 20011380 | STUD;CYL HEAD;GE 221X1001-1 | L | 4.000 | EA |
| \|--- | 20267660 | SUPER O LUBE;2OZ TUBE;PARKER;SLUBE 884-2 | L | 1.000 | EA |
| \|--- | 20267661 | SUPER O LUBE;40LB BUCKET;PARKER | L | 1.000 | EA |
| \|--- | 20247176 | TENSIONER;PIN;PULLER NUT;2270-15 | L | 4.000 | EA |
| \|--- | 20106102 | VALVE ASSY,COMPRESSION;GE 321X1053-1 | L | 1.000 | EA |
| \|--- | 20106103 | WASHER,SEALING;GE 321X1040 | L | 1.000 | EA |
| \|--- | 20011353 | WASHER;CYL STUD;GE 221X1002 | L | 4.000 | EA |
| \|--- | | 1000431100 | N | 1.000 | EA |

Figure D.5: RTIO Power Assembly System Bill Of Materials (BOM)

# Appendix E

# HSE incident report extracts

Statement Date: 19.05.2012 Lead Investigator: Sumesh Duvvuru
See incident reporter detail
Full investigation report, has been finalised and actions from that report are in place. Victaulic installation program has ceased and review of the fleet has been completed, Ge to provide feedback on this issue before project can continue
Note created by Laurence Healey ( LHEALEY )
On 07.AUG.2012 at 02:14:58 ( UK )
Note created by Mark Hornhardt ( HORNHAMK )
On 09.JAN.2013 at 16:15:33 ( AUSWA )
----------------------------------------------------------------------------
Incident Investigation
Bolts not tightened sufficiently
----------------------------------------------------------------------------
Statement Date: 25.04.2012 Incident Reporter: Craig Herschell
******* Long Description ********
Approximately 3000 litres of fuel spilled from Locomotive number 815(
(Trail Loco)
Train number Y 698, Tag number 23.
Fuel leak reported at
0400 25/04/2012.
Fuel leak was reported from Marandoo.
Fuel leak was
due to a loose fuel block connected to the fuel pump.
Fuel leak was
tracedback to Rosella siding.
Locomotive 8150 was shutdown at Marandoo
to avoid further contamination.
No contamination observed beyond
Marandoo.
******* Risk Reduction Ideas ********
Ensure retention tank alarm on Locomotives are operative.
Share
learnings amongst Locomotive Drivers to observe operation of locomotive during roll by situations.
Note created by Craig Herschell ( CHERSCHELL )
on 25.APR.2012 at 15:30:01 ( AUSWA )
Full investigation report, has been finalised and actions from that report are in place. Victaulic installation program has ceased and

Figure E.1: Fuel system HSE incident - Fuel Leak - Locomotive 8150, 25 April 2012

Statement Date: 21.10.2013 Lead Investigator: Shaun Pikor
Replaced Cracked High Pressure Fuel Line due to defective batch from GE
Note created by Shaun Pikor ( PIKORSE )
On 21.OCT.2013 at 11:28:52 ( AUSWA )
----------------------------------------------------------------------------
Statement Date: 04.03.2013 Incident Reporter: Chad Killmore
High Pressure Fuel Leak
----------------------------------------------------------------------------

Figure E.2: Fuel system HSE incident - Fuel Leak - Locomotive 8133, 04 March 2013

# Appendix F

# Component Usage Rates

| Material Description | INJECTOR,FUEL;323X1003-1 | | |
|---|---|---|---|
| | | | |
| **Sum of Number of Items** | **Column Labels** | | |
| **Row Labels** | **Unscheduled** | **Scheduled** | **Grand Total** |
| **2013** | | | |
| Jan | | 36 | 36 |
| Feb | | 12 | 12 |
| Mar | | 96 | 96 |
| Apr | 2 | 12 | 14 |
| Jun | 1 | | 1 |
| Jul | | 36 | 36 |
| Aug | | 72 | 72 |
| Sep | | 84 | 84 |
| Oct | 1 | 48 | 49 |
| Nov | | 51 | 51 |
| Dec | 1 | 56 | 57 |
| **2014** | | | |
| Jan | -1 | 62 | 61 |
| Feb | | 24 | 24 |
| Mar | 1 | 48 | 49 |
| **Grand Total** | **5** | **637** | **642** |

Figure F.1: Fuel Injector usage details

| Material Description | PUMP,FUEL;HP;332X1001-1 | | |
|---|---|---|---|
| | | | |
| **Sum of Number of Items** | **Column Labels** | | |
| **Row Labels** | **Unscheduled** | **Scheduled** | **Grand Total** |
| **2013** | | | |
| Feb | | 36 | 36 |
| Mar | | 12 | 12 |
| Apr | | 12 | 12 |
| Jul | | 24 | 24 |
| Sep | 2 | | 2 |
| Oct | 0 | | 0 |
| Nov | 1 | | 1 |
| Dec | 1 | 12 | 13 |
| **2014** | | | |
| Jan | -1 | 36 | 35 |
| Feb | | 48 | 48 |
| Mar | | 24 | 24 |
| **Grand Total** | **3** | **204** | **207** |

Figure F.2: High Pressure Fuel Pump usage details

| Material Description | PUMP,FUEL BOOST;84A215237P6 | | |
|---|---|---|---|
| | | | |
| Sum of Number of Items | Column Labels | | |
| Row Labels | Unscheduled | Scheduled | Grand Total |
| ⊟2013 | | | |
| Feb | 4 | 1 | 5 |
| Mar | 4 | | 4 |
| Apr | 2 | 3 | 5 |
| May | 0 | | 0 |
| Jun | 3 | 1 | 4 |
| Aug | 1 | | 1 |
| Oct | 3 | | 3 |
| Nov | 1 | | 1 |
| Dec | 2 | | 2 |
| ⊟2014 | | | |
| Mar | 1 | 0 | 1 |
| Grand Total | 21 | 5 | 26 |

Figure F.3: Fuel Transfer Pump usage details

| Row Labels | BOLT;M12 X 1.75 X 60MM LG;GEC;115P21060 | CAP;GUARD;CYL STUD;GE 221X1038-1 | CLAMP;EXHAUST;GEC;228X1004-1 | GASKET;HEAD;CYLINDER;84E930252P1 | GASKET;STRONG BACK TO TOPDECK;315X1000-2 | HEAD,ENGINE;GE 321X1034 | NUT,STRETCH;M36X2,321X1059 | O-RING;321X1002 | O-RING;50MM ID,VITON,215X1016 | O-RING;GE 321X1024 | PISTON AND CONROD ASSY;322X1006-1 | POWER ASSY;UPPER;322X1007 | RING KIT;PISTON;350X1005 | ROCKER COVER;321X1058 | SEAL,O-RING;GE 41A219499ABP246 | SPACER;GEC;115X2594 | STUD;CYL HEAD;GE 221X1001-1 | VALVE ASSY,COMPRESSION;GE 321X1053-1 | WASHER,SEALING;GE 321X1040 | WASHER;CYL STUD;GE 221X1002 | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ⊟2013 | | | | | | | | | | | | | | | | | | | | | |
| Jan | | | | | 2 | | | | 1 | | 1 | 1 | 1 | | 6 | | 1 | | | | 13 |
| Feb | | | | | 2 | 1 | | | 1 | | 2 | 2 | 1 | | 15 | 1 | | | | | 25 |
| Mar | 1 | 1 | | 1 | 3 | 1 | 1 | | 2 | | 2 | 3 | 3 | 1 | 13 | | 1 | | | | 33 |
| Apr | | | | | | 3 | | | | | | | | | 10 | | | 1 | 2 | | 16 |
| May | | | | | | | | | | | | | | | 3 | | | | | | 3 |
| Jun | | 2 | | | 3 | | | | 2 | | 1 | 4 | 3 | | 3 | | 2 | | | 1 | 21 |
| Jul | | | | | 1 | | | 1 | | | | 1 | | | 4 | | | 1 | | | 8 |
| Aug | | | | | 1 | | | | 1 | | 1 | 3 | 1 | | 5 | | | | | | 12 |
| Sep | | 2 | | | 1 | | 1 | | 2 | 1 | 1 | 3 | 2 | 1 | 3 | | 2 | | 2 | 1 | 22 |
| Oct | | 1 | | 1 | 3 | | 1 | | 1 | | | 1 | | | 1 | | 3 | | | | 12 |
| Nov | | | 1 | | 2 | | | | 1 | | 1 | 2 | 2 | | | 1 | | | | | 10 |
| Dec | | | 2 | | 1 | | | | 1 | | | 1 | 1 | | 1 | | | | | | 7 |
| ⊟2014 | | | | | | | | | | | | | | | | | | | | | |
| Jan | | | | | | | | | | | | | | | 1 | | | | | | 1 |
| Feb | | | 1 | | 2 | | | | 1 | | | 2 | 2 | | | | | | | | 8 |
| Mar | | | | | 1 | | 1 | | | | | | | | | | 1 | | | 1 | 4 |
| Grand Total | 1 | 6 | 4 | 2 | 22 | 5 | 4 | 1 | 13 | 1 | 9 | 23 | 16 | 2 | 65 | 2 | 10 | 2 | 4 | 3 | 195 |

Figure F.4: Power Assembly component usage details. All usage is unscheduled.

| Years | Work Order Basic Start Date | AIR CLEANER,GE 41E901373G2 | BOLT;115X2722 | BOLT;GEC;N14BP29036 | CONNECTING PIECE;40MM LG,241X1002 | COUPLING;VICT,GASKET,8",41B548215ACP14 | DUCT,FLEX;E/O TURBO AIR;84C603145ABP1 | DUCT,TURBO INLET,GE 41A202118P1,9" | DUCT;GEC;84A213197AMP7 | FAN;AIR TO AIR;GEC;84A213551P3 | FILTER ELEMENT;AIR INTAKE;GE;84A204576P2 | FLANGE;8.5";HEAT EXCH;84B518058AGP1 | FLANGE;WATER OUTLET,341X1010 | GASKET,GE 115X2587-1,TURBO TO MUFFLER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2013 | Jan | | | | | | | 1 | 3 | | | | | 1 |
| | Feb | | | 1 | 1 | 1 | 1 | 2 | 1 | | | 1 | | 2 |
| | Mar | | | | 1 | 1 | | | | | | 1 | | |
| | Apr | | | | | | | 1 | | | | 3 | | 1 |
| | May | | | | | | | 2 | 1 | 2 | | | | 1 |
| | Jun | | | | 1 | | | 1 | 2 | | | | 2 | 1 |
| | Jul | | | | 3 | | | 2 | 4 | | | | | 2 |
| | Aug | | | | 1 | | | | 2 | | | | | |
| | Sep | 1 | | | 2 | 2 | | 4 | 3 | 2 | 1 | 1 | 1 | 4 |
| | Oct | | 2 | | | | | 4 | | | 1 | | | 3 |
| | Nov | | | | 1 | | | | | | | | | |
| | Dec | | | | | | | 2 | | | 1 | | | 2 |
| 2014 | Jan | | | 1 | | | | 2 | 1 | 1 | | | | 2 |
| | Feb | | 1 | | | | | 1 | | | | | | 1 |
| | Mar | | | | | | | | | | | | | |
| | Apr | | 2 | | | | | | 1 | | | | | |
| | May | | | | | | | 2 | | | | | | 2 |
| | Jun | 1 | 1 | | 1 | 1 | | 1 | | 1 | | 1 | | 1 |
| Grand Total | | 2 | 6 | 2 | 11 | 5 | 1 | 25 | 18 | 6 | 3 | 7 | 3 | 23 |

| Years | Work Order Basic Start Date | GASKET,GE 126X1787-1,MUFFLER MOUNTING | GASKET,GE 128X1413-1,TURBO | GASKET,VICT COUPLING,4",EPDM | GASKET;0.062" THICK;84A214635ABP1 | HOSE ASSY;GEINT;84B531666P2 | HOSE;COALESCER;LG;GE 328X1013-2 | HOSE;FITTED;TURBO OIL;GE 326X1023 | INSTALL KIT;TURBO;TIER 2;350X1044 | INTERCOOLER ASSY;AIR;GE 84D712244ALG1 | INTERCOOLER,WATER BASED;GE 84D712639AGG1 | MUFFLER ASSY;GEC;84C608414G2 | O-RING,GE 115X2420,TURBO OIL SUPPLY PIPE | O-RING,GE 115X2448,TURBO OIL DRAIN PIPE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2013 | Jan | 1 | 1 | 1 | 1 | | | 1 | | | | | 1 | 1 |
| | Feb | 2 | 2 | 2 | 3 | | 2 | | 1 | | | | 2 | 2 |
| | Mar | | | | | | | | | | | | | |
| | Apr | 2 | 2 | 1 | 1 | 2 | 2 | | | | 2 | | 1 | 1 |
| | May | 1 | 1 | 1 | 2 | | 1 | | | | 1 | | 1 | 1 |
| | Jun | 3 | 1 | 2 | 1 | | 1 | | | | | | 1 | 1 |
| | Jul | 3 | 2 | 3 | 3 | | 2 | 3 | | | 2 | | 2 | 2 |
| | Aug | 4 | | | 1 | | | | | | 2 | | | |
| | Sep | 4 | 4 | 4 | 4 | | 4 | | | | 2 | 2 | 4 | 4 |
| | Oct | 3 | 3 | 3 | 3 | | 2 | | | | 2 | 2 | 3 | 3 |
| | Nov | 1 | | | | | | | | | | 1 | | |
| | Dec | 2 | 2 | 2 | 2 | | 1 | | | | 1 | | 2 | 2 |
| 2014 | Jan | 2 | 2 | 3 | 2 | | 2 | | | | | | 2 | 2 |
| | Feb | 1 | 1 | 2 | 1 | | 1 | | | | 1 | | 1 | 1 |
| | Mar | 2 | | | 1 | | | 1 | | | | 2 | | |
| | Apr | | | 3 | 1 | | 3 | | | | | 1 | 1 | |
| | May | 2 | 2 | 2 | 2 | 1 | 2 | | | | | | 2 | 2 |
| | Jun | 2 | 1 | 1 | 1 | | 1 | | | 1 | 2 | | 1 | 1 |
| Grand Total | | 35 | 24 | 30 | 29 | 3 | 24 | 5 | 1 | 1 | 15 | 8 | 24 | 23 |

| Years | Work Order Basic Start Date | O-RING;360MM OD,315X1025 | O-RING;GE 241X1010 | O-RING;GE 41A219499ABP217 | O-RING;GE 41A219499ABP334 | O-RING;GE 41A219499ABP374 | O-RING;GE 41A219499ABP382 | O-RING;GE 41A219499ABP464 | O-RING;TURBO DISCH DUCT,41A219499ABP370 | SEAL,GE 115X2620,TURBO WTR OUTLET,EPDM | SEAL;GEINT;41A224140P4 | SPACER;CABLE;1/2IN BY 5/8IN;2-1/8IN | SPACER;GEC;115X2594 | TURBOCHARGER;GEC;326X1152 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2013 | Jan | | 1 | | | | | | 2 | 1 | 1 | | | 1 |
| | Feb | | 2 | | | | | | 2 | 2 | 2 | | | |
| | Mar | | | | | 1 | | | | | | | | |
| | Apr | | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | | | 1 |
| | May | | 1 | | | 1 | | | 2 | 1 | 1 | | | 1 |
| | Jun | | 1 | | | | | | 1 | 1 | 2 | | | 1 |
| | Jul | | 2 | 1 | 1 | | 1 | 1 | 3 | 2 | 4 | | | 2 |
| | Aug | 1 | | | | | | | | | 3 | | | |
| | Sep | | 4 | 2 | 2 | 5 | 2 | 2 | 5 | 4 | 3 | | | 3 |
| | Oct | | 3 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 4 | | | 2 |
| | Nov | | | | | 1 | | | 1 | | 1 | | 1 | |
| | Dec | | 2 | 1 | 1 | | 1 | 1 | 2 | 2 | 2 | | | 2 |
| 2014 | Jan | | 2 | | | 2 | | | 2 | 2 | 2 | | | 2 |
| | Feb | | 1 | 1 | 1 | | 1 | | 1 | 1 | 1 | | | 1 |
| | Mar | | | | | | | | | | 1 | | | |
| | Apr | 1 | | | | | | | | | 2 | | 1 | |
| | May | | 2 | | | 1 | | | 2 | 2 | 2 | | | 2 |
| | Jun | | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 |
| Grand Total | | 2 | 23 | 9 | 9 | 16 | 9 | 8 | 28 | 23 | 33 | 1 | 2 | 19 |

Figure F.5: Combustion air system component usage details. All usage is unscheduled.

| Material | Usage | Comments |
|---|---|---|
| O-RING,GE 115X2448,TURBO OIL DRAIN PIPE | 63 | Due to turbocharger failures. |
| GASKET,VICT COUPLING, 4",EPDM | 56 | Due to turbocharger and water pump failures. |
| O-RING;TURBO DISCH DUCT,41A219499ABP370 | 52 | Some failed; primarily due to turbocharger failures. |
| SEAL,GE 115X2620,TURBO WTR OUTLET,EPDM | 43 | Due to turbocharger failures. |
| GASKET,GE 126X1787-1,MUFFLER MOUNTING | 33 | Due to muffler and turbocharger failures. |
| SEAL;GEINT;41A224140P4 | 33 | Due to muffler and turbocharger failures; one oil leak occurred. |
| BOLT;115X2722 | 30 | Known issue (cyclic thermal stresses causing fatigue); upgraded design being implemented. |
| CONNECTING PIECE;40MM LG,241X1002 | 29 | Not part of the combustion air system - cooling |
| O-RING;GE 41A219499ABP334 | 27 | Due to turbocharger and intercooler failures. |
| GASKET;0.062" THICK;84A214635ABP1 | 27 | Due to turbocharger failures. |
| O-RING;GE 41A219499ABP374 | 26 | Some failed; most due to other component failures. |
| DUCT;GEC;84A213197AMP7 | 25 | Due to manufacture misalignment issue. This issue has been rectified. |
| GASKET,GE 128X1413-1,TURBO | 24 | Due to turbocharger failures. |
| O-RING,GE 115X2420,TURBO OIL SUPPLY PIPE | 24 | Due to turbocharger failures. |
| O-RING;GE 241X1010 | 23 | Due to turbocharger failures. |
| GASKET,GE 115X2587-1,TURBO TO MUFFLER | 21 | Due to turbocharger failures. |
| HOSE;COALESCER;LG;GE 328X1013-2 | 20 | Due to manufacture issue that has been rectified. |
| DUCT,TURBO INLET,GE 41A202118P1,9" | 19 | Due to turbocharger failures. |
| TURBOCHARGER;GEC;326X1152 | 19 | Design issues including resonance, soft rotor shafts and bearing failures. |
| BOLT;GEC;N14BP29036 | 15 | One set used on a turbocharger failure. |
| FILTER ELEMENT;AIR INTAKE;GE;84A204576P2 | 15 | 3 sets changed on turbocharger failures. |
| INTERCOOLER,WATER BASED;GE 84D712639AGG1 | 13 | Mostly accounted for by turbocharger and engine failures. Only 4 genuine intercooler failures. |
| FLANGE;8.5";HEAT EXCH;84B518058AGP1 | 12 | Due to fatigue cracking. |

Figure F.6: Investigation of combustion air system high-usage items

# Appendix G

# Reliability Modelling Supporting Information

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Loco | Loco Class | Work Order | Work Order Type | Installation Date | Work Order Basic Start Date | Time in service | Number of items and direction | Were the items returned to the store? | Number of elements in system | Replacement? | Failure Mode | Delivery status | Material | Material Description |
| 2 | 8100 | EVO | 12894818 | PM01 | 1/02/2008 | 6/09/2010 | 948.00 | 12 | FALSE | 12 | TRUE | 1 | @08@ | 20011435 | PUMP,FUEL;HI |
| 3 | 8101 | EVO | 15318034 | PM01 | 1/02/2008 | 3/07/2013 | 1979.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 4 | 8102 | EVO | 13120526 | PM01 | 1/02/2008 | 25/01/2011 | 1089.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 5 | 8103 | EVO | 32035771 | PM03 | 1/02/2008 | 12/09/2011 | 1319.00 | 2 | FALSE | 12 | FALSE | Corroded | @08@ | 20011435 | PUMP,FUEL;H |
| 6 | 8104 | EVO | 22416335 | PM02 | 1/02/2008 | 1/04/2011 | 1155.00 | 1 | FALSE | 12 | FALSE | Unknown | @08@ | 20011435 | PUMP,FUEL;H |
| 7 | 8104 | EVO | 13619430 | PM01 | 1/04/2011 | 9/01/2012 | 283.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 8 | 8105 | EVO | 13619433 | PM01 | 1/02/2008 | 27/05/2012 | 1577.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 9 | 8106 | EVO | 13062156 | PM01 | 1/02/2008 | 29/11/2010 | 1032.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;HI |
| 10 | 8107 | EVO | 13619435 | PM01 | 1/02/2008 | 8/10/2011 | 1345.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 11 | 8108 | EVO | 13619436 | PM01 | 1/02/2008 | 1/09/2011 | 1308.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 12 | 8108 | EVO | 15294759 | PM01 | 1/09/2011 | 29/07/2013 | 697.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 13 | 8109 | EVO | 13120100 | PM01 | 1/02/2008 | 17/01/2011 | 1081.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 14 | 8110 | EVO | 13619437 | PM01 | 1/08/2008 | 13/07/2012 | 1442.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 15 | 8111 | EVO | 13619439 | PM01 | 1/08/2008 | 7/07/2012 | 1436.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 16 | 8112 | EVO | 13619480 | PM01 | 1/08/2008 | 12/08/2012 | 1472.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 17 | 8113 | EVO | 13120531 | PM01 | 1/08/2008 | 6/06/2011 | 1039.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 18 | 8114 | EVO | 13665395 | PM01 | 1/08/2008 | 17/12/2012 | 1599.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 19 | 8115 | EVO | 13619481 | PM01 | 1/08/2008 | 27/12/2012 | 1609.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 20 | 8116 | EVO | 13619484 | PM01 | 1/08/2008 | 24/10/2011 | 1179.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 21 | 8117 | EVO | 22639422 | PM02 | 1/08/2008 | 28/10/2011 | 1183.00 | 1 | FALSE | 12 | FALSE | Unknown | @08@ | 20011435 | PUMP,FUEL;H |
| 22 | 8117 | EVO | 13619486 | PM01 | 28/10/2011 | 13/02/2012 | 108.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 23 | 8118 | EVO | 13619489 | PM01 | 1/08/2008 | 12/07/2012 | 1441.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 24 | 8119 | EVO | 13120779 | PM01 | 1/08/2008 | 30/05/2011 | 1032.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 25 | 8120 | EVO | 14119173 | PM01 | 1/08/2008 | 6/08/2012 | 1466.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 26 | 8121 | EVO | 13120535 | PM01 | 1/08/2008 | 23/03/2011 | 964.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 27 | 8121 | EVO | 15954566 | PM01 | 23/03/2011 | 27/01/2014 | 1041.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |
| 28 | 8122 | EVO | 13619495 | PM01 | 1/08/2008 | 30/07/2012 | 1459.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011435 | PUMP,FUEL;H |

Figure G.1: High Pressure Fuel Pump reliability modelling data

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Lo | Loco Cla | Work Order | Work Order Typ | Installation Date | Work Order Basic Start Dat | Time in service | Number of items and directi | Were the items returned to the store? | Number of Elements in System | Replace ment? | Failure Mode | Delivery status | Material | Material Description |
| 3 | 8100 | EVO | 32688923 | PM03 | 17/05/2011 | 5/10/2013 | 872.00 | 1 | FALSE | 12 | FALSE | Unknown - Flames from stack - | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 5 | 8101 | EVO | 13894831 | PM01 | 18/01/2010 | 23/01/2012 | 735.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 6 | 8101 | EVO | 15654575 | PM01 | 23/01/2012 | 28/10/2013 | 644.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 8 | 8102 | EVO | 14531911 | PM01 | 24/01/2011 | 1/11/2012 | 647.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 10 | 8103 | EVO | 32035771 | PM03 | 4/01/2010 | 12/09/2011 | 616.00 | 2 | FALSE | 12 | FALSE | Unknown - numerous electrica | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 11 | 8103 | EVO | 15376419 | PM01 | 12/09/2011 | 15/07/2013 | 672.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 13 | 8104 | EVO | 13118798 | PM01 | 11/01/2010 | 31/01/2011 | 385.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 14 | 8104 | EVO | 22307569 | PM02 | 31/01/2011 | 9/05/2011 | 98.00 | 12 | FALSE | 12 | FALSE | Unknown - RX | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 15 | 8104 | EVO | 14506666 | PM01 | 9/05/2011 | 19/03/2013 | 680.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 16 | 8104 | EVO | 23263770 | PM02 | 19/03/2013 | 2/04/2013 | 14.00 | 1 | FALSE | 12 | FALSE | Unknown | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 17 | 8105 | EVO | 22423806 | PM02 | 24/09/2009 | 7/04/2011 | 560.00 | 11 | FALSE | 12 | FALSE | Unknown | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 18 | 8105 | EVO | 13581716 | PM01 | 7/04/2011 | 26/09/2011 | 172.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 19 | 8105 | EVO | 15144132 | PM01 | 26/09/2011 | 22/07/2013 | 665.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 21 | 8106 | EVO | 14346365 | PM01 | 17/01/2011 | 18/10/2012 | 640.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 23 | 8107 | EVO | 13581717 | PM01 | 27/01/2010 | 8/10/2011 | 619.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 24 | 8107 | EVO | 15160999 | PM01 | 8/10/2011 | 5/08/2013 | 667.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 26 | 8108 | EVO | 13581718 | PM01 | 4/01/2010 | 2/01/2012 | 728.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 27 | 8108 | EVO | 15593170 | PM01 | 2/01/2012 | 25/11/2013 | 693.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 29 | 8109 | EVO | 22300830 | PM02 | 11/01/2010 | 17/12/2010 | 340.00 | 1 | FALSE | 12 | FALSE | Unknown - RX | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 30 | 8109 | EVO | 13118783 | PM01 | 17/12/2010 | 3/05/2011 | 137.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 31 | 8109 | EVO | 14850866 | PM01 | 3/05/2011 | 25/03/2013 | 692.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 33 | 8110 | EVO | 14119168 | PM01 | 22/10/2010 | 9/07/2012 | 626.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 35 | 8111 | EVO | 13118801 | PM01 | 21/04/2010 | 16/06/2011 | 421.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 36 | 8111 | EVO | 15102018 | PM01 | 16/06/2011 | 19/08/2013 | 795.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 38 | 8112 | EVO | 13813485 | PM01 | 5/07/2010 | 5/11/2011 | 488.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 39 | 8112 | EVO | 22656451 | PM02 | 5/11/2011 | 14/11/2011 | 9.00 | 1 | FALSE | 12 | FALSE | Unknown - Due to low oil pres | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 40 | 8112 | EVO | 15593171 | PM01 | 14/11/2011 | 16/09/2013 | 672.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 42 | 8113 | EVO | 13619680 | PM01 | 8/02/2010 | 26/09/2011 | 595.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |
| 43 | 8113 | EVO | 15189029 | PM01 | 26/09/2011 | 6/08/2013 | 680.00 | 12 | FALSE | 12 | TRUE | | @08@ | 20011412 | INJECTOR,FUEL;323X1003-1 |

Figure G.2: High Pressure Fuel Injector reliability modelling data

# Appendix H

# Reliability-Centered Maintenance Overview for Participants

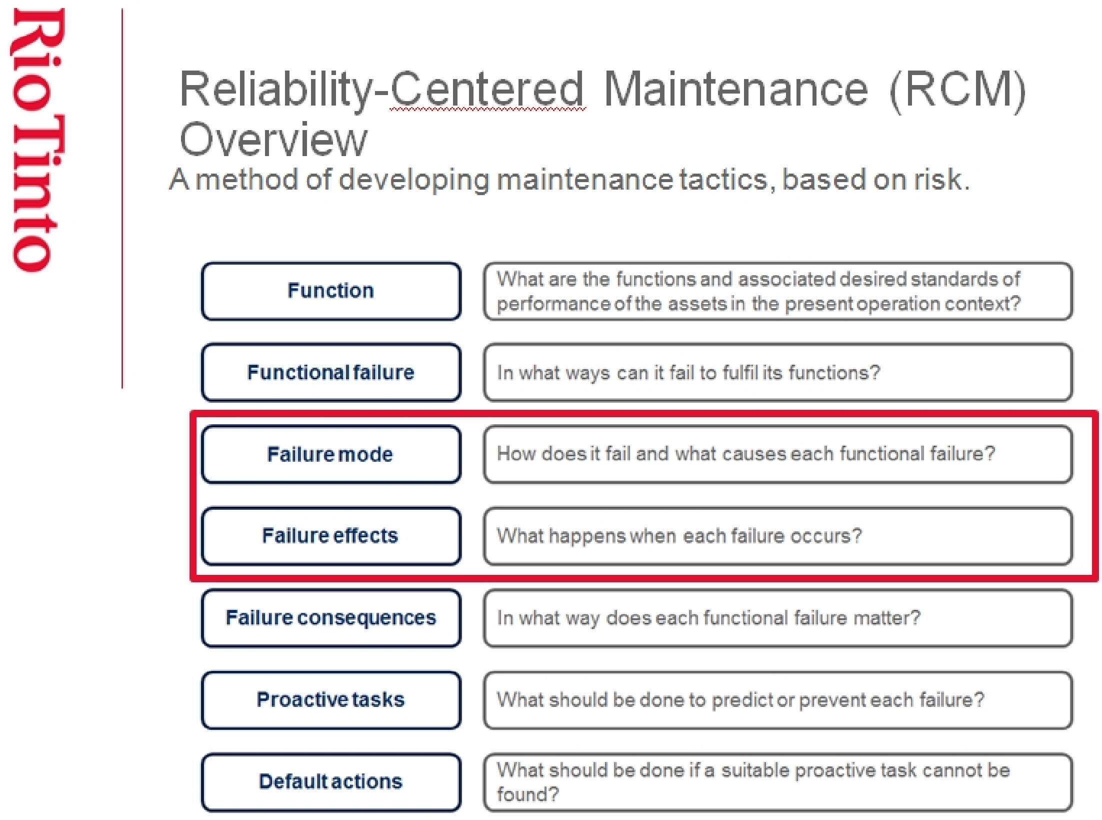


Figure H.1: Slide 1

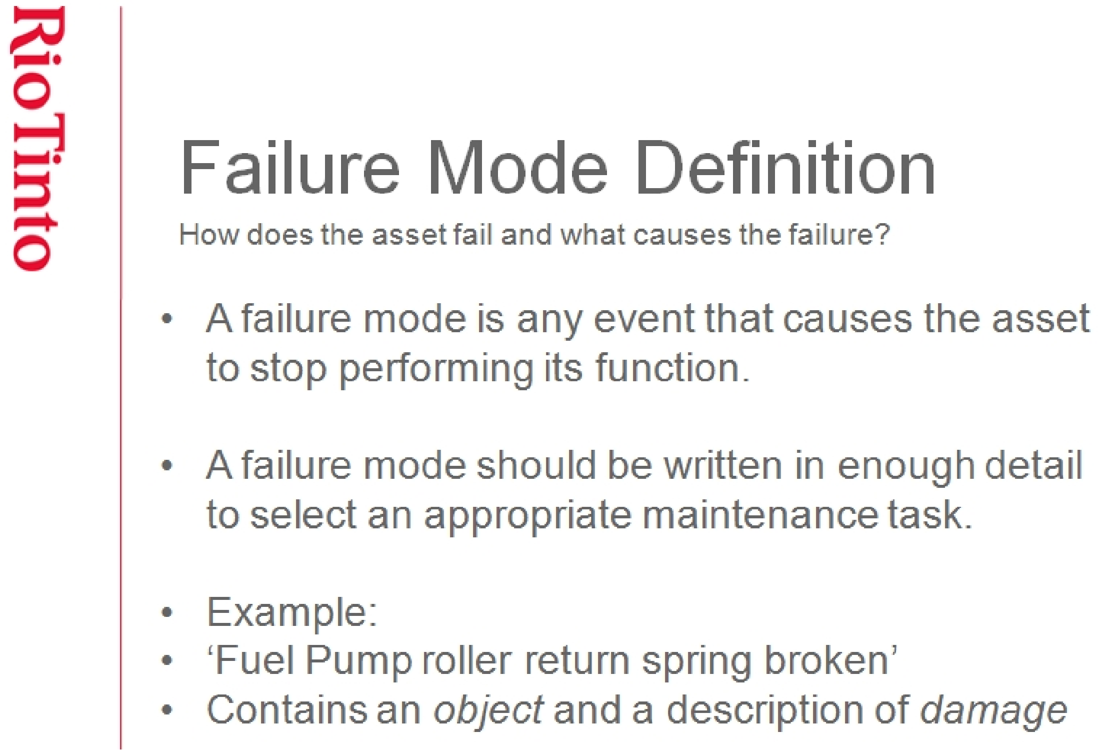


Figure H.2: Slide 2

RioTinto

## Failure Effects

What happens when the failure mode occurs?

The failure effect description includes:

- What evidence is there that the failure has occurred?
- In what ways does it pose a threat to HSE?
- What secondary physical damage is caused to the asset, and other equipment when the failure occurs?
- What must be done to repair the failure?

Figure H.3: Slide 3

RioTinto

## Points to note -

- The focus of RCM is on maintaining ***functions***, not the asset itself
- Failure modes and effects should be defined as if ***no*** maintenance is being performed
- RCM is intended to be based on common sense – what is likely to occur, within reason

Figure H.4: Slide 4

RioTinto

# EVO Engine RCM

High Pressure Fuel Pumps

- Are we wasting money by changing out the HP Pumps at 11,000 hours?
- How could the pumps fail if we extended the service life?

- 10 known failures of EVO HP Pumps since '08
  - 3 Due to guide pin falling out
  - 1 Corroded (no further detail available)
  - 1 Solenoid not engaging
  - 1 Leaking
  - 4 Unknown

- Dash 9 common failure modes
  - Broken spring
  - Pushrod lash incorrectly set

Figure H.5: Slide 5

| **Failure Mode**<br><br>**What is the object that fails, and how does it fail?** | **Failure Effects**<br><br>**What evidence is there of the failure?**<br>**Does it pose a threat to safety or the environment?**<br>**Does it affect production or operations?**<br>**What physical damage is caused by the failure?**<br>**What must be done to repair the failure?** |
|---|---|
| Valve tappet loose;<br>not torqued ref SAP:(incorrect valve adjustment)<br>Note that the new bridge style doesn't have a guide, needs to be set precisely - good workmanship is critical.<br>16907523<br>18011672<br>18386472<br>16930509<br>20555167 | **What evidence is there of the failure?**<br>The failure progresses to damaged valve guide/seal, allowing blowby into the rocker cover. This causes a COPS fault. May bend or break the valve, causing catastrophic engine failure and a COPS.<br>**Does it pose a threat to safety or the environment?**<br>Nil.<br>**Does it affect production or operations?**<br>Yes, the loco will require shutting down, causing a delay.<br>**What physical damage is caused by the failure?**<br>Hammer on the top of the rocker and physical damage. End up fatigueing and breaking the valve/broken valve. requires power assembly replacement. Could be damage to pushrod, but pretty rare. Will damage the valve guide/seal, leading to blowby into rocker box & cops.<br>**What must be done to repair the failure?**<br>Power assembly replacement. |

Figure H.6: FMEA worksheet extract

## Appendix I

# Rio Tinto Reliability Solution (RTRS) Reliability-Centered Maintenance (RCM) Screenshots

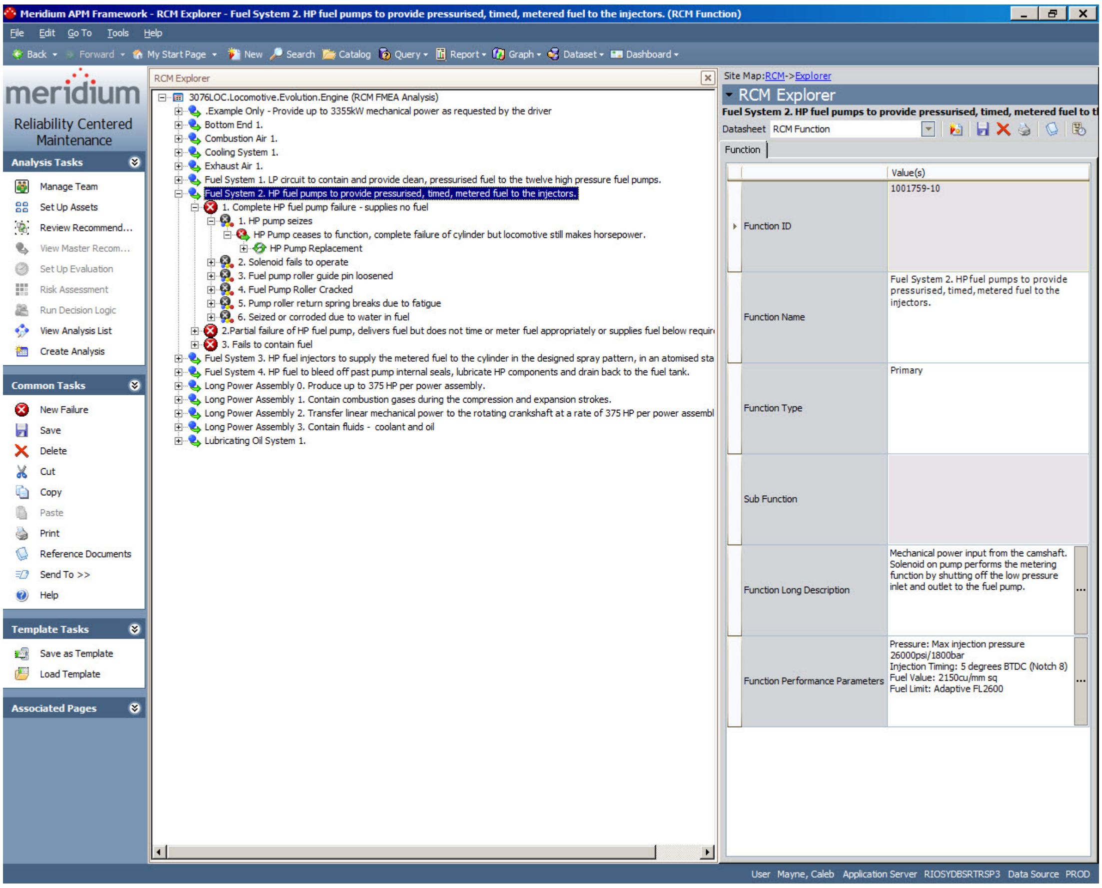


Figure I.1: RTRS Function Definition

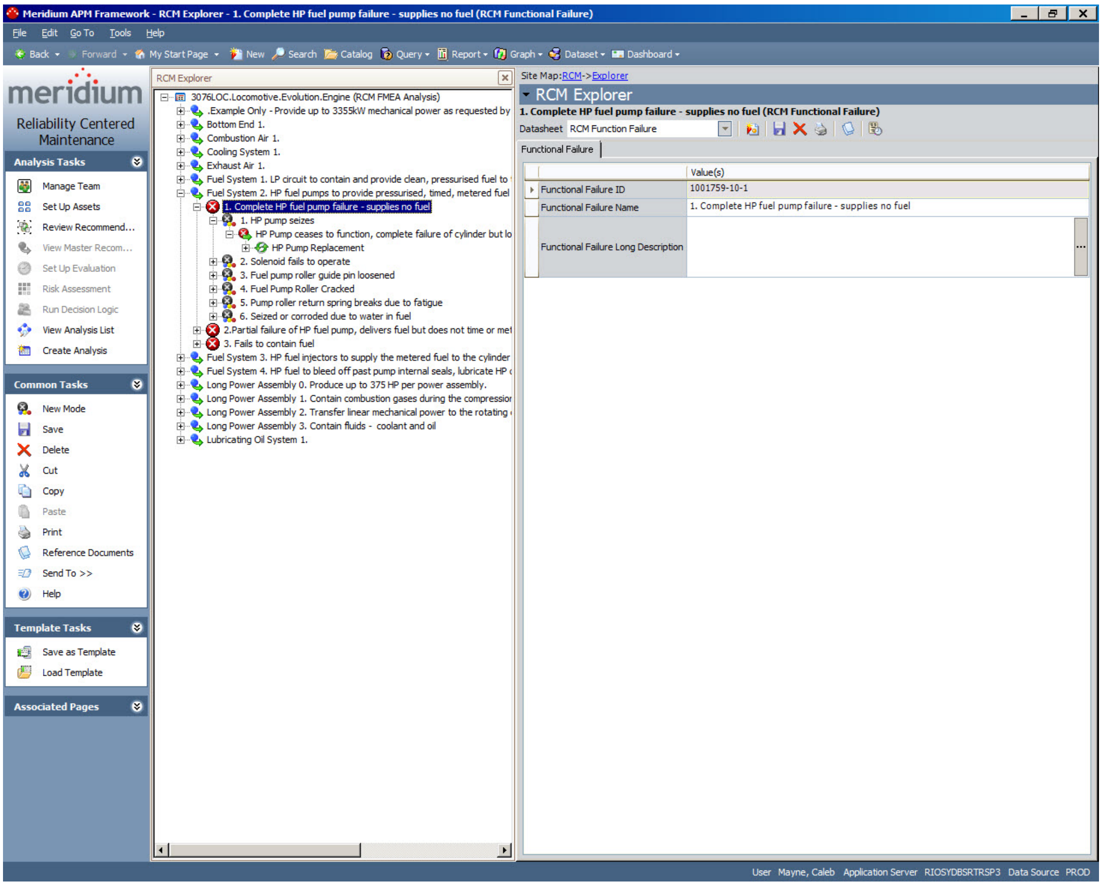

Figure I.2: RTRS Functional Failure Definition

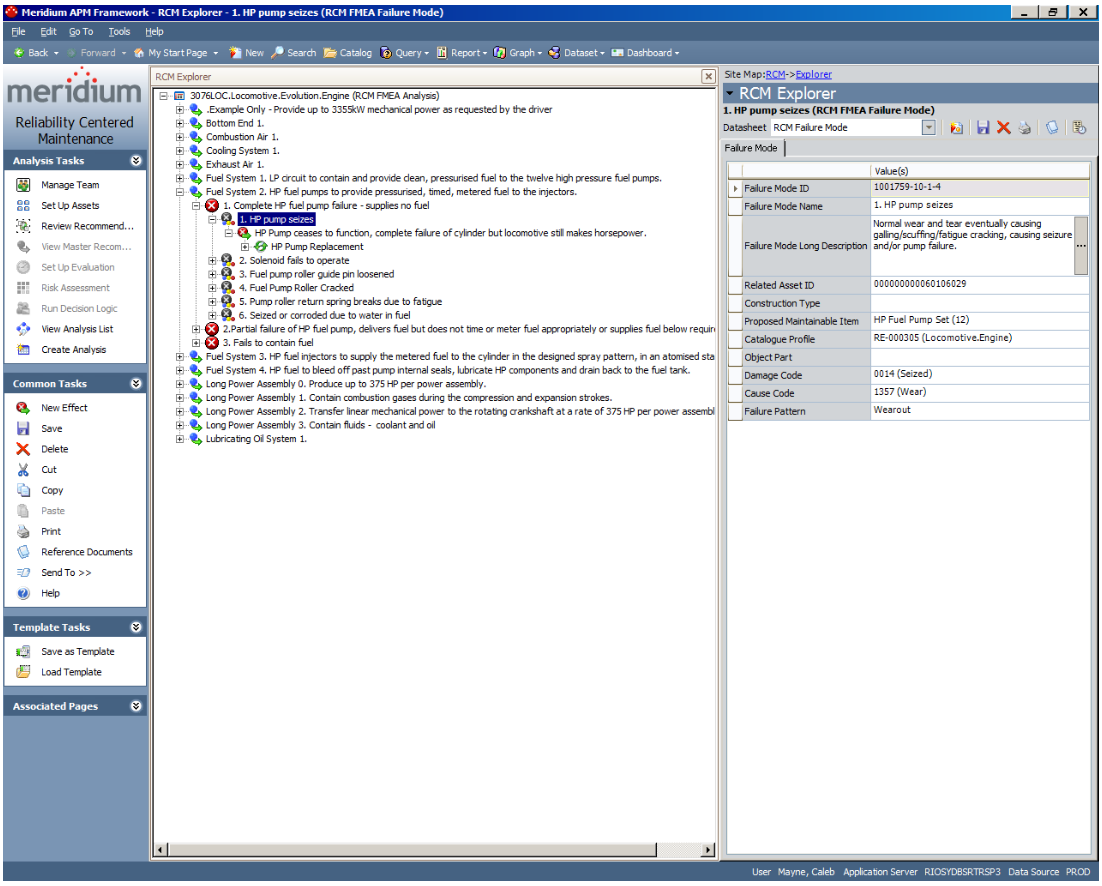


Figure I.3: RTRS Failure Mode Definition

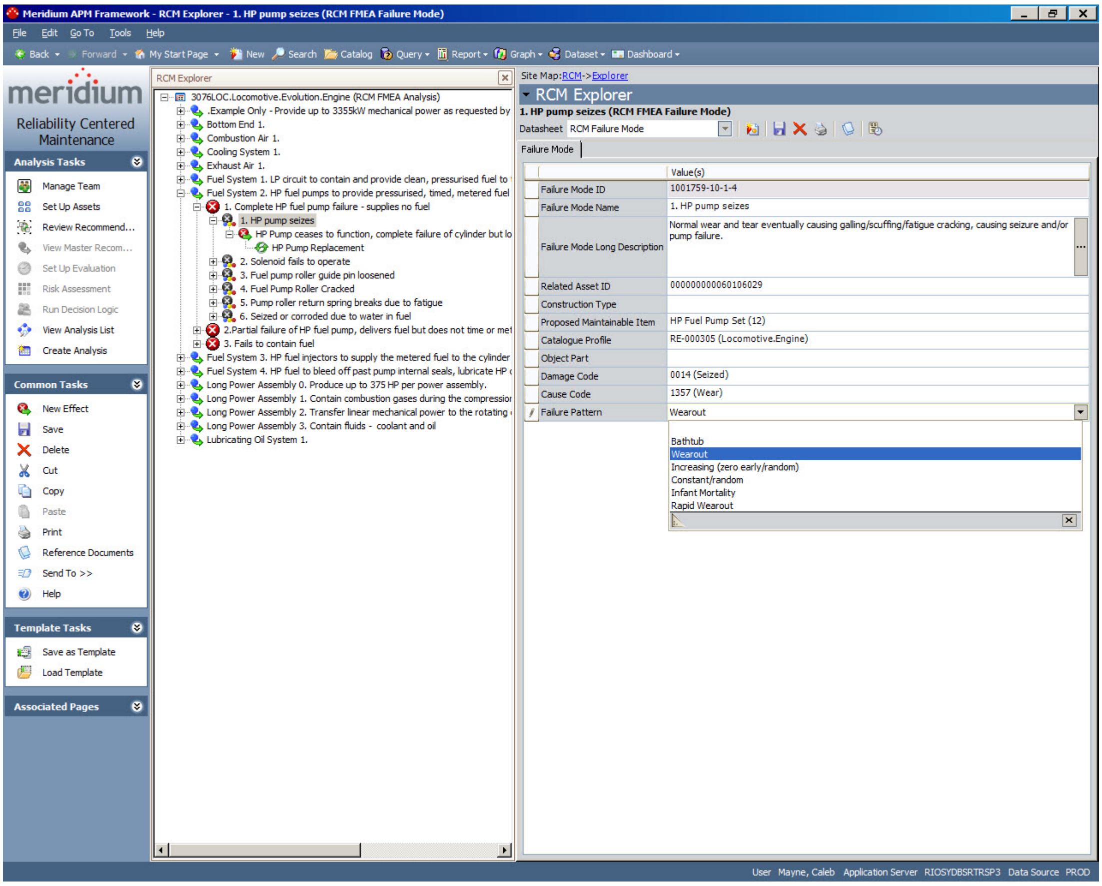


Figure I.4: RTRS Failure Mode Pattern Options

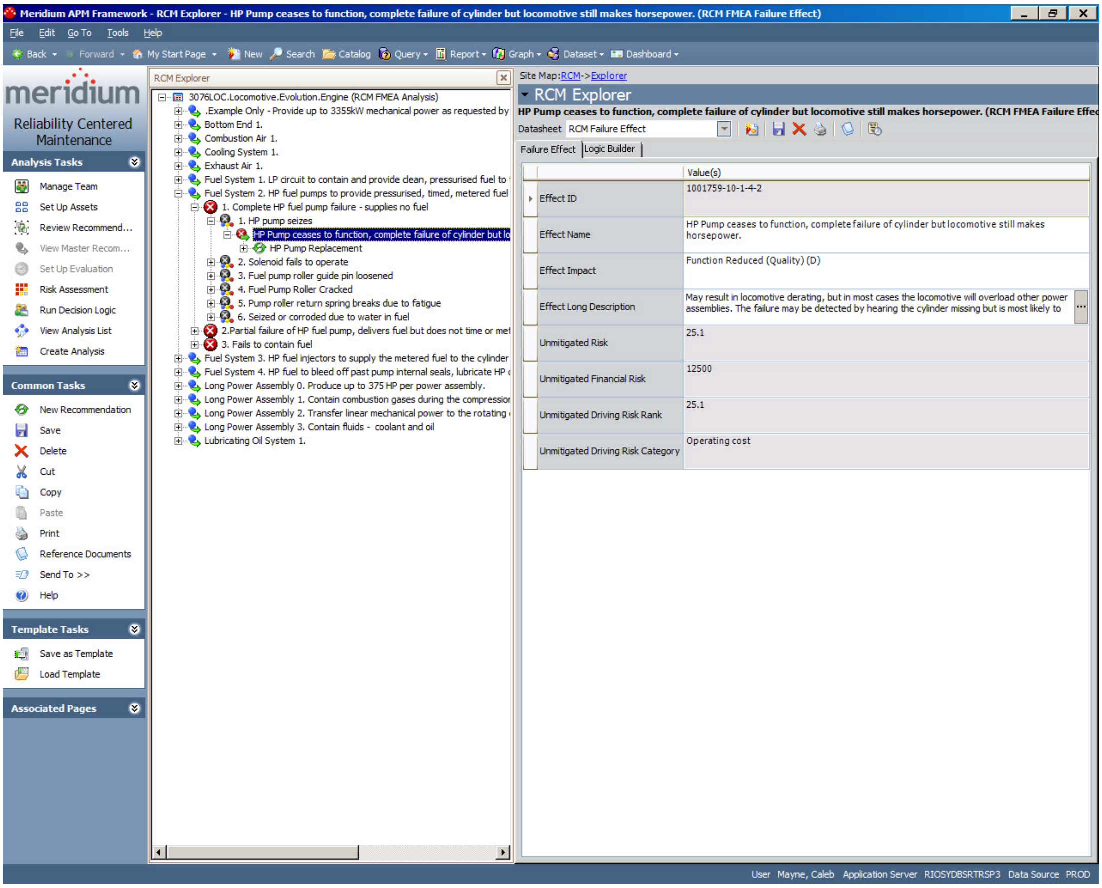


Figure I.5: RTRS Failure Effect Definition

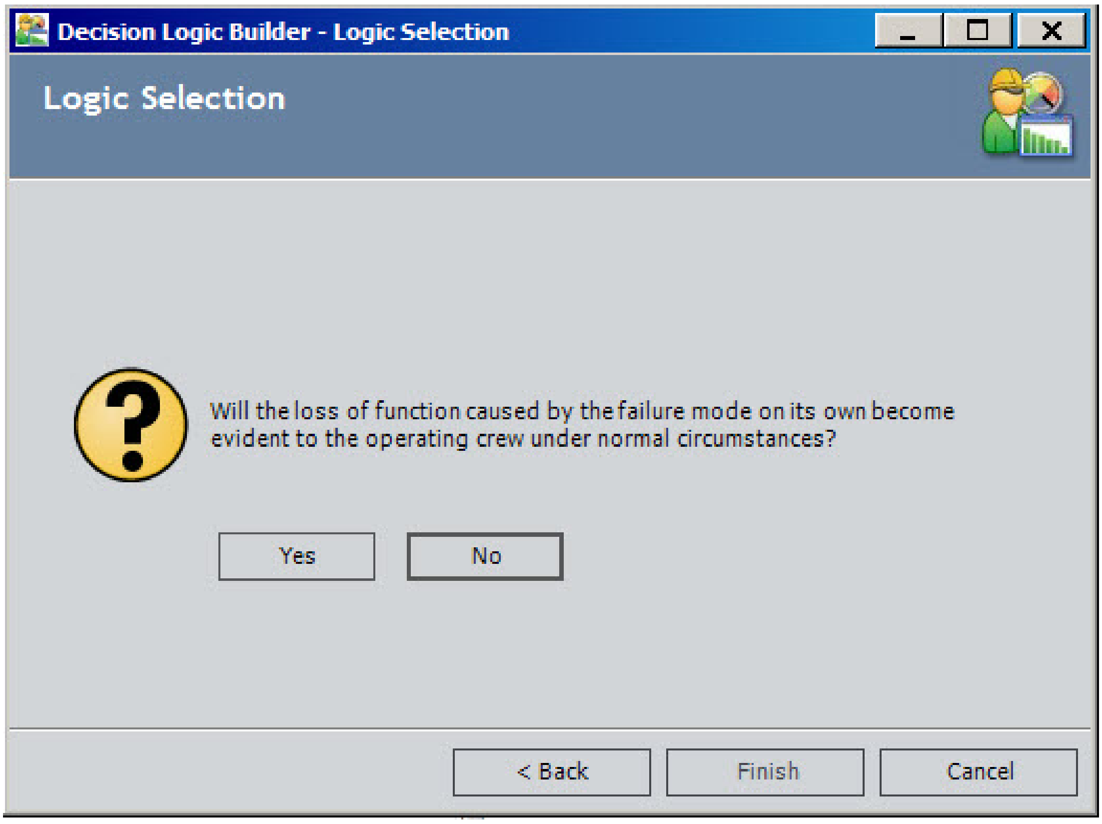


Figure I.6: RTRS Decision Logic


Figure I.7: RTRS Unmitigated Risk Assessment

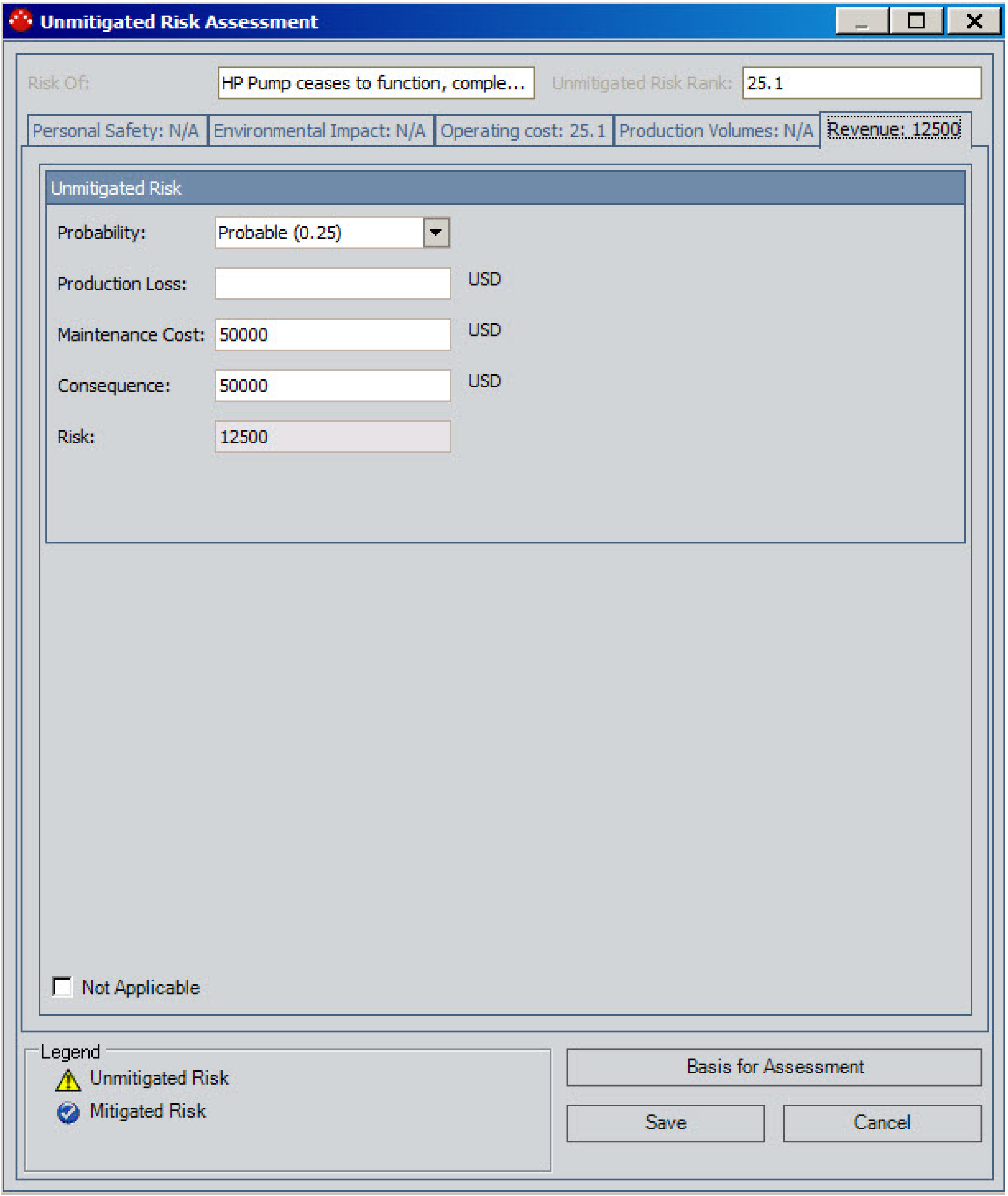


Figure I.8: RTRS Unmitigated Risk Assessment, page 2

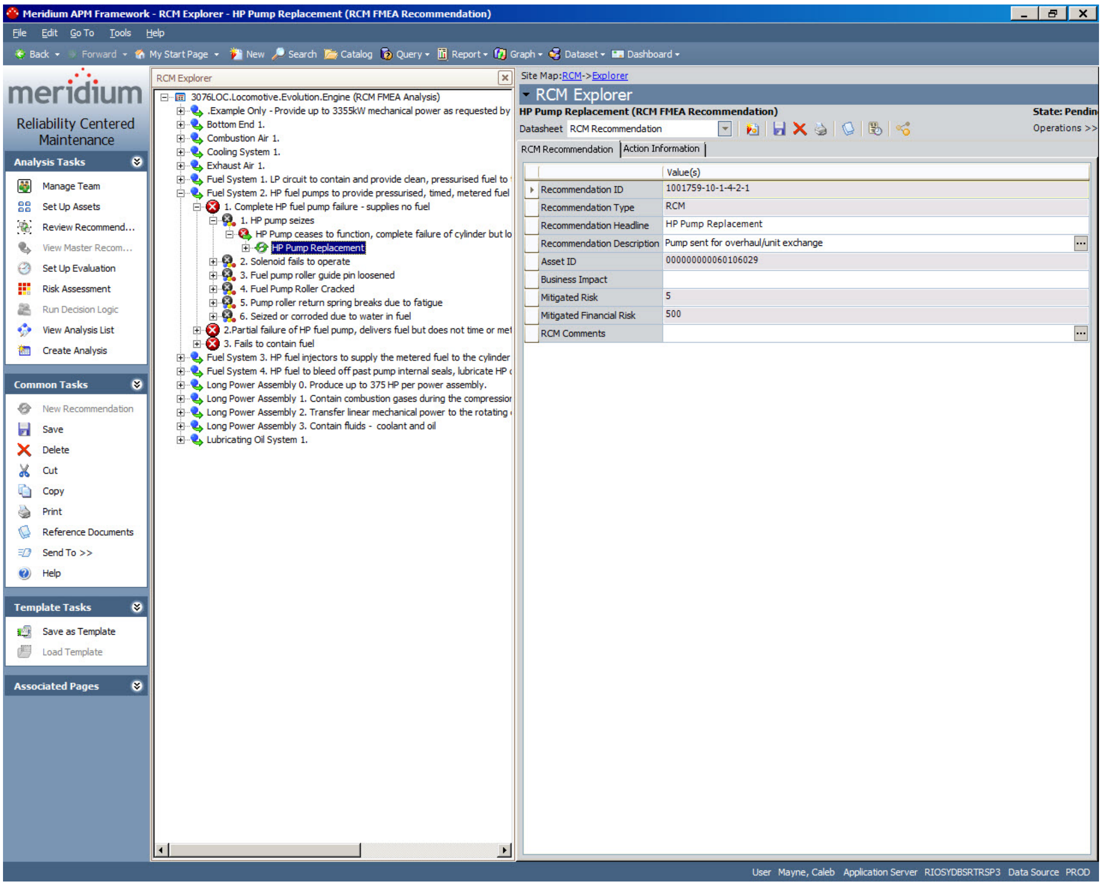


Figure I.9: RTRS Recommendation Definition

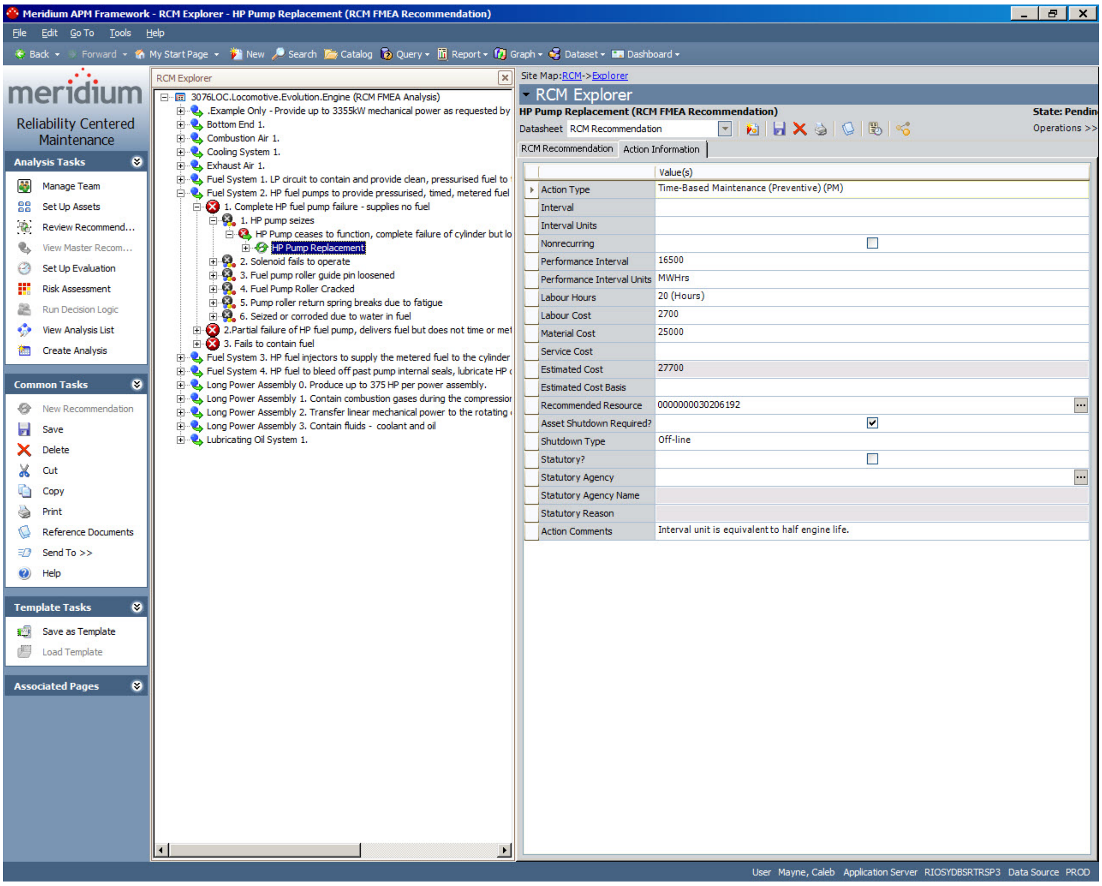


Figure I.10: RTRS Recommendation Definition, page 2

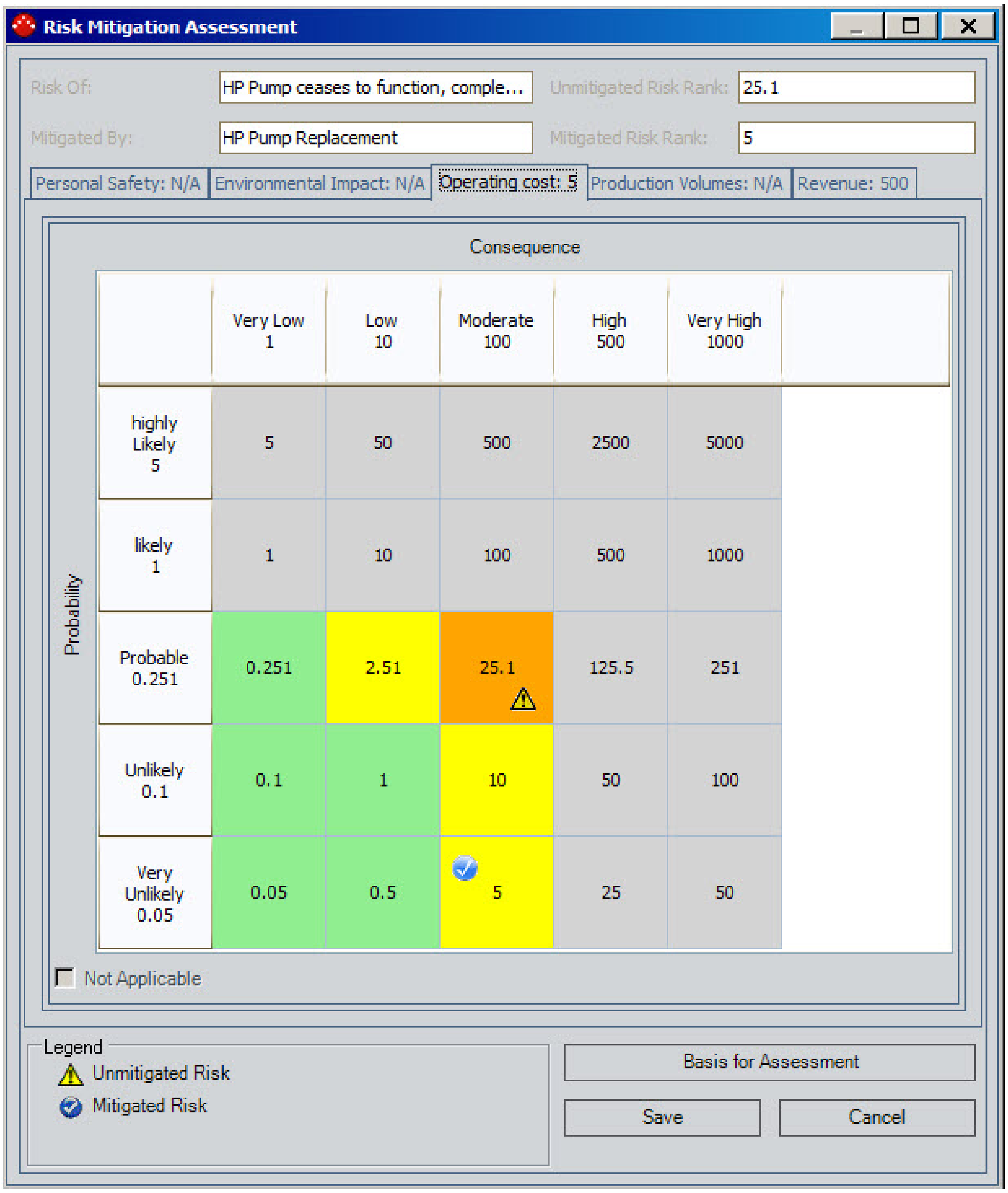


Figure I.11: RTRS Mitigated Risk Assessment

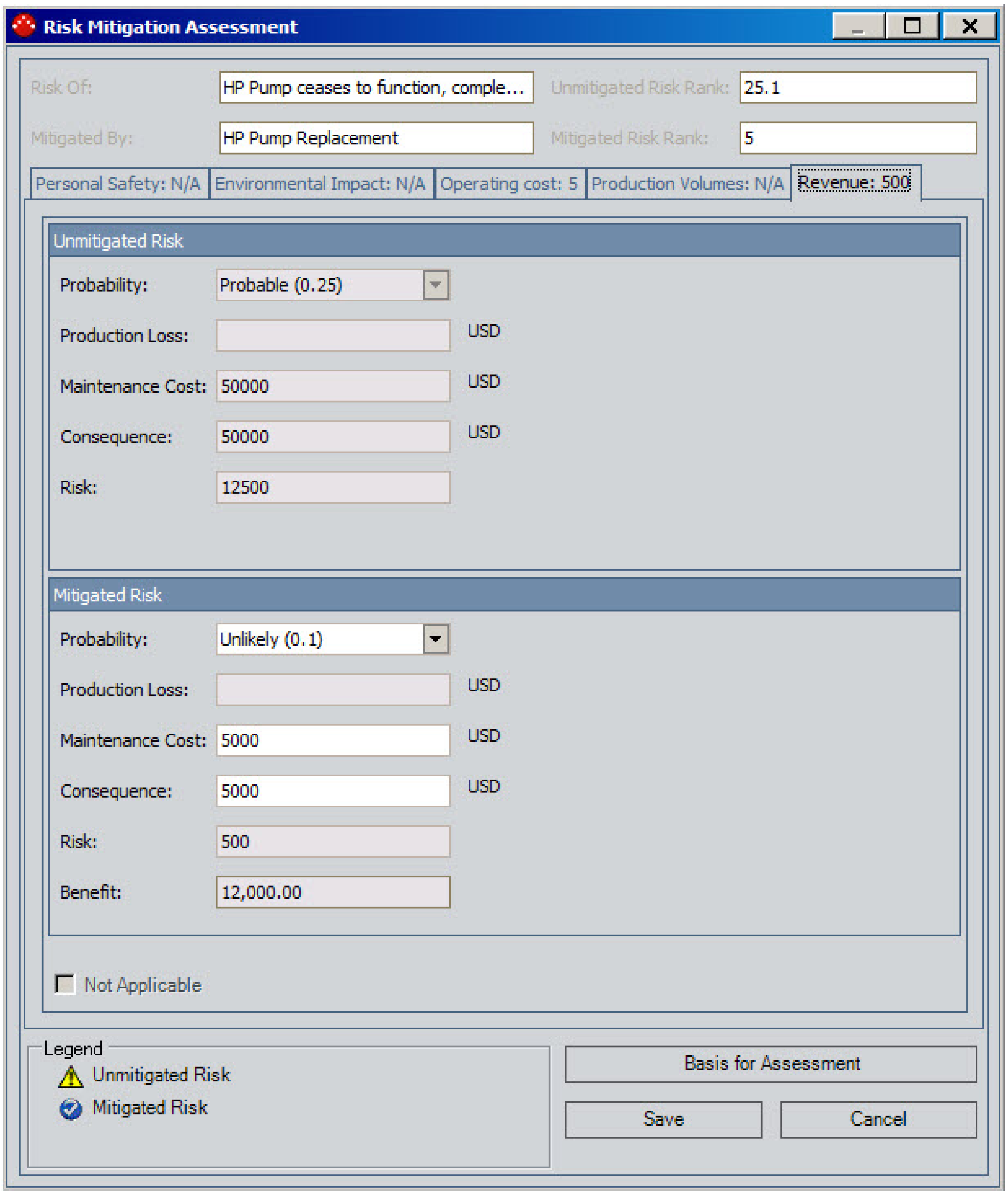


Figure I.12: RTRS Mitigated Risk Assessment, page 2

# Appendix J

# Failure modes and effects analysis short description summary

| Failure Mode Id | Effect Name |
|---|---|
| 01.01.01. Fuel transfer pump fails | Locomotive shuts down |
| 01.02.01. Fuel transfer pump vanes worn | Locomotive logs a low fuel pressure alarm |
| 01.02.02. Return fuel pressure regulating valve is out of adjustment. | Locomotive logs a low fuel pressure alarm |
| 01.03.01. Fuel strainer or filters are blocked | Locomotive logs a low fuel pressure alarm; won't load in higher notches |
| 01.04.01. Return fuel pressure regulating valve is out of adjustment. | Fuel transfer pump internal relief valve activates, returning excess fuel to the fuel tank. |
| 01.05.01. Fuel filter blocked | HP components (injectors and pumps) will fail prematurely due to high levels of fuel contaminants (dirt). |
| 01.05.02. Fuel filter damaged, allowing dirt to enter system | HP components (injectors and pumps) will fail prematurely due to high levels of fuel contaminants (dirt). |
| 01.07.02. Hot return fuel from engine entering fuel tank directly next to fuel intake. | Fuel transfer pump fails; Locomotive shuts down |
| 01.08.01. Moisture condenses in the fuel tank, contaminating the fuel | High pressure fuel system components damaged; susceptible to seizure, premature wear and corrosion. |
| 02.01.01. HP Fuel pump internal seals worn | Individual cylinder efficiency drops; other cylinders make extra power |
| 02.01.02. Fuel is not timed correctly causing harsh combustion and overloading | COPS fault; Locomotive shuts down. |
| 02.02.01. HP pump seizes | HP Pump ceases to function, complete failure of cylinder but locomotive still makes horsepower. |
| 02.02.02. Solenoid fails to operate | Power assembly will no longer produce power but locomotive will still make full horsepower. |
| 02.02.03. Fuel pump roller guide pin loosened | HP pump ceases to function and is severely damaged along with the camshaft |
| 02.02.04. Fuel Pump Roller Cracked | HP pump ceases to function and is severely damaged along with the camshaft and power assembly strongback |
| 02.02.05. Pump roller return spring breaks due to fatigue | Secondary damage caused to engine |
| 02.02.06. Seized or corroded due to water in fuel | Entire set of HP pumps seizes, locomotive failure. |
| 03.02.01. Injector atomising nozzles worn | Spray pattern quality is reduced, decreasing fuel efficiency and power |
| 03.02.02. Injector nozzle blocked or partially blocked due to carbon build up. | Cylinder does not perform efficiently |
| 03.02.03. Injector seals worn allowing excessive back leagage | Spray pattern quality is reduced, decreasing fuel efficiency and power |
| 03.03.01. Injector needle lift pressure low due to broken or softened spring | Cylinder does not perform efficiently, engine blows black smoke. |
| 03.03.02. Injector needle seizes due to excessive wear | Injector doesn't seal; leaks fuel into cylinder before and after intended fuel injection window |
| 03.03.03. Injector needle, seat, pressure pin worn. | Cylinder does not perform efficiently, engine blows black smoke. |
| 03.03.04. Needle and seat degraded | Cylinder does not perform efficiently, engine blows black smoke. |
| 03.03.05. Seized due to lack of lubrication due to water in fuel | Injector doesn't seal; leaks fuel into cylinder before and after intended fuel injection window |
| 03.03.06. Seized or cracked nozzle due to accelerated wear due to dirt ingress | Injector doesn't seal; leaks fuel into cylinder before and after intended fuel injection window |
| 04.01.01. Flexible Fuel return hose rubs through against compressed air pipe below the platform level | Significant fuel spill - 1000 Litres |

| Failure Mode Id | Effect Name |
|---|---|
| 04.01.02. Hose rubs through due to contact on another component combined with vibration | Fuel leak fills the retention tank, locomotive is shut down. |
| 04.01.03. Rubber hose cracks or splits due to perished rubber | Fuel leak fills the retention tank, locomotive is shut down. |
| 04.01.04. Injector O-Rings leaking | High pressure fuel leak on the engine |
| 04.01.05. Fuel line joint bolts left loose following maintenance | Fuel leak |
| 04.01.06. HP Pump joint seal failure | Fuel leak |
| 04.01.07. HP fuel line crack | Fuel leak |
| 04.01.08. Low pressure fuel hose bracket broken due to fatigue. | Fuel leak fills the retention tank, locomotive is shut down. |
| 04.01.09. Incompatible hose material or fitting is used and fails prematurely. | Fuel leak fills the retention tank, locomotive is shut down. |
| 05.01.01. Injector is loose, o-ring seals wear due to vibration, permitting coolant to enter the lubricating fuel line | Water leaks through HP components and drains back to tank |
| 06.01.01. Cylinder liner failure due to fatigue cracking | COPS fault; Locomotive shuts down. |
| 06.01.02. Piston and Cylinder seizure due to oil starvation | COPS fault; Locomotive shuts down. |
| 06.01.03. Piston failure due to fatigue cracking | COPS fault; Locomotive shuts down. |
| 06.01.04. Piston skirt wear allowing misalignment and overloading | Piston fracture; COPS fault; locomotive shuts down |
| 06.01.05. Piston seizes due to warped cylinder due to uneven head stud torque. | COPS fault; Locomotive shuts down. |
| 06.01.06. Piston sealing ring land or piston skirt cracked due to excessive piston-cylinder clearance | COPS fault; locomotive shuts down |
| 06.01.07. Piston sealing ring broken due to incorrect fitment. | COPS fault; locomotive shuts down |
| 06.01.08. Piston/cylinder liner scoring. Root cause unknown. | COPS fault; locomotive shuts down |
| 06.01.09. Piston seizes due to lack of lubrication due to glazed bore | COPS fault; locomotive shuts down |
| 06.01.10. Piston cracking due to harsh combustion and overloading. | COPS fault; locomotive shuts down |
| 06.01.11. Piston component seizure due to overheating | COPS fault; locomotive shuts down |
| 07.01.01. Pushrod snapped. Root cause unknown. | Low oil pressure alarm; locomotive shuts down |
| 07.01.02. Valve bridge loose; fitted incorrectly | Rocker cover broken; engine oil leak |
| 07.01.03. Valve tappet loose; not fully torqued due to open ended spanner fouling | Rocker cover broken; engine oil leak |
| 07.01.04. Valve tappet loose; not torqued properly | Rocker cover broken; engine oil leak |
| 07.01.05. Valve train rocker shaft bolts come loose due to insufficient torque. | Rocker cover broken; engine oil leak |
| 07.01.06. Valve bridge seized. Root cause unknown. | Rocker cover broken; engine oil leak |
| 07.01.07. Crosshead roller cracked due to introduced defect | Power assembly ceases to function; oil is diluted causing a low lube oil pressure alarm. |

Figure J.1: FMEA short descriptions, part 1

| Failure Mode Id | Effect Name |
|---|---|
| 07.01.08. Crosshead roller cracked due to fatigue | Power assembly ceases to function; oil is diluted causing a low lube oil pressure alarm. |
| 08.01.01. Connecting rod failure due to fatigue cracking | Catastrophic engine failure |
| 08.01.02. Premature connecting rod fatigue failure | Catastrophic engine failure |
| 08.01.03. Insufficient bolt pretension causing fatigue cracking in the connecting rod, bolts or bearing. | Catastrophic engine failure |
| 08.02.01. Bearing seizure due to cavitation damage | COPS fault, crankshaft damage |
| 08.02.02. Bearing failure due to fatigue cracking | COPS fault, crankshaft damage |
| 08.02.03. Bearing Seizure due to lubricant contamination | COPS fault, crankshaft damage |
| 08.02.04. Bearing failure due to electrical discharge | COPS fault, crankshaft damage |
| 08.02.05. Bearing failure due to assembly error | COPS fault, crankshaft damage |
| 09.01.01. Cylinder liner accelerated wear | COPS fault; locomotive shuts down |
| 09.01.02. Cylinder liner wears allowing excessive blow-by | COPS fault; locomotive shuts down |
| 09.01.03. Piston Sealing Rings lost tension or worn | COPS fault; locomotive shuts down |
| 09.02.01. Power assembly head cracked due to thermal stress and vibration fatigue cracking | Power assembly ceases to produce power |
| 09.02.02. Valve corroded due to combustion by-products | Power assembly ceases to produce power |
| 09.02.03. Valve disc burnt - secondary damage | Power assembly ceases to produce power |
| 09.02.04. Valve disc burnt due to insufficient valve lash. | Power assembly ceases to produce power |
| 09.02.05. Valve fatigue fracture due to excessive valve lash | Power assembly ceases to produce power |
| 09.02.06. Valve fatigue fracture initiated by fretting corrosion between the valve stem and valve stem keeper. | Power assembly ceases to produce power |
| 09.02.07. Valve spring fatigue fracture due fretting corrosion between the spring and and cylinder head. | COPS fault; locomotive shuts down |
| 09.02.08. Valve spring fatigue fracture due surface finish damage. | COPS fault; locomotive shuts down |
| 09.02.09. Valve stem seizure due to gum build-up due to degraded lubricating oil. | Power assembly ceases to produce power |
| 09.02.10. Valve stem seizure due to gum build-up due to excessive idling | Power assembly ceases to produce power |
| 09.03.01. Decompression plug washer failed | Combustion gases leak during the compression and expansion stroke. |
| 09.03.02. Fire ring sealing area worn | Combustion gases leak during the compression and expansion stroke. |
| 10.01.01. Cylinder liner perforation due to cavitation corrosion | COPS fault; locomotive shuts down |
| 10.01.02. Cylinder liner shoulder seal embrittlement/hardening due to exposure to heat and chemical | Coolant leak into engine sump and/or combustion chamber |
| 10.01.03. Cylinder liner shoulder seal fails prematurely | Coolant leak into engine sump and/or combustion chamber |

| Failure Mode Id | Effect Name |
|---|---|
| 10.01.04. Head gasket leaking due to erosion/corrosion on head and/or strongback | Engine fluid leakage |
| 10.01.05. Head gasket leaking due to poor assembly. | Engine fluid leakage. |
| 10.01.06. Head stud broken due fatigue cracking | Engine fluid leakage. |
| 10.01.07. Head stud broken due to fatigue due to too many exposed threads. | Engine fluid leakage. |
| 10.01.08. Head Stud broken due to overloading from previous broken stud. | Engine fluid leakage. |
| 10.01.09. Valve guide worn due to normal wear | Oil is blown out the exhaust; rocker cover pressurised causing oil leak. |
| 10.01.10. Rocker cover cracked. Root cause unknown - likely to be secondary damage. | Engine oil leak from the power assembly. |
| 11.01.01. Turbo bearing failure due to fatigue | Locomotive derates or shuts down on COPS fault. |
| 11.01.02. Turbo bearing failure due to overload | Locomotive derates or shuts down on COPS fault. |
| 11.01.03. Turbine blade failure | Locomotive derates or shuts down on COPS fault. |
| 11.01.04. Turbo compressor wheel high cycle fatigue failure due to vibration resonance. | Locomotive derates or shuts down on COPS fault. |
| 11.01.05. Turbo shaft failure | Locomotive derates or shuts down on COPS fault. |
| 11.01.06. Turbo washed by rain water; goes out of balance | Locomotive derates or shuts down on COPS fault; turbo fails due to imbalance |
| 11.01.07. Foreign object strikes turbine disc or compressor wheel. | Locomotive derates or shuts down on COPS fault. |
| 11.01.08. Baggy air filter clogged | Locomotive performance limited; logs an alarm |
| 11.01.09. Turbine disc is eroded due to particles in the exhaust gas | Locomotive power and efficiency is reduced |
| 11.01.10. Exhaust bellows installed back to front causing turbo failure. | Leads to turbocharger failure and engine damage; loco shuts down on COPS fault. |
| 11.02.01. Turbo discharge o-ring leaking boost air | Boost air leak |
| 11.02.02. Turbo flange bolts cracked | Exhaust gas leak, turbo capacity lowered |
| 11.02.03. Turbo inlet flange cracked due to cyclical thermal stress fatigue | Exhaust gas leak, turbo capacity lowered |
| 11.02.04. Turbo discharge/ WBIC duct cracked | Locomotive suffers from turbo surging |
| 11.02.05. Turbo discharge/WBIC flexible duct split due to misalignment | Locomotive suffers from turbo surging |
| 11.02.06. Air based intercooler leaking boost air due to fatigue cracking or erosion. | Locomotive suffers from turbo surging |
| 11.02.07. 8.5" Aluminium Air to Air Intercooler Inlet flange cracked due to fatigue | Locomotive suffers from turbo surging |
| 11.02.09. WBIC inlet flange o-ring leaking | Boost air leak |
| 11.03.01. Air based intercooler fan bearings seized | Loco Air inlet manifold temperature high; loco derates |
| 11.03.02. Air based intercooler fan failed; insulation broken down causing a ground fault. | Loco Air inlet manifold temperature high; loco derates |

Figure J.2: FMEA short descriptions, part 2

| Failure Mode Id | Effect Name |
|---|---|
| 11.03.03. Air based intercooler clogged by dirt or debris | Loco Air inlet manifold temperature high; loco derates |
| 11.03.04. Water based intercooler blocked or fouled | Not analysed further. |
| 12.01.01. Baggy air filter exterior is contaminated by debris | Leads to turbocharger failure and engine damage; loco shuts down on COPS fault. |
| 12.01.02. Baggy air filter torn | Leads to turbocharger failure and engine damage; loco shuts down on COPS fault. |
| 12.01.03. Spin filters clogged | Baggy air filters prematurely clogged |
| 12.01.04. Turbo inlet duct cracked due to rubber ageing | Leads to turbocharger failure and engine damage; loco shuts down on COPS fault. |
| 13.01.01. Turbo oil supply line perforated. | Oil leak |
| 13.01.02. Turbo coolant drain seal leaking | Coolant leak |
| 13.01.03. Turbo oil drain seal leaking | Oil leak |
| 13.01.04. Water based intercooler leaking coolant due to cavitation | Coolant leaks into the combustion air supply; buildup of coolant solids on intercooler and engine components |
| 13.01.05. Water Based Intercooler leaking coolant due to fatigue cracking | Coolant leaks into the combustion air supply; buildup of coolant solids on turbo |
| 13.01.06. Water based intercooler leaking due to corrosion | Coolant leaks into the combustion air supply; buildup of coolant solids on turbo |

Figure J.3: FMEA short descriptions, part 3

# Appendix K

# Recommendations Summary

| Recommendation Headline | Failure Mode Id | Recommended Interval | Recommended Resource Description | Total Unmitigated Risk | Total Mitigated Risk | Current Maintenance Task | Current Task Interval | Current Risk | Risk Delta (Current Risk-Total Mitigated Risk) | Change Level |
|---|---|---|---|---|---|---|---|---|---|---|
| CBM: Inspect and renew O-rings whenever joints are disturbed for maintenance | 04.01.06. HP Pump joint seal failure | | Diesel Mechanic | 30 | 15 | CBM: Inspect and renew O-rings whenever joints are disturbed for maintenance | N/A | 15 | 0 | None |
| CBM: Perform Dead Cylinder Test | 02.02.02. Solenoid fails to operate | 3 Months | Diesel Mechanic | 5 | 0.05 | CBM: Perform Dead Cylinder Test | 4 months | 0.05 | 0 | Minor |
| CBM: Perform Weak Cylinder Test | 02.01.01. HP Fuel pump internal seals worn | 3 Months | Diesel Mechanic | 0.251 | 0.05 | SCH: HP Pump Replacement | 11000 MWHrs | 0.05 | 0 | Minor |
| CBM: Acoustic Emissions (AE) monitoring | 02.01.01. HP Fuel pump internal seals worn | | | 45.451 | 10.12 | SCH: HP Pump Replacement | 11000 MWHrs | 10.6 | 0.48 | None |
| | 02.02.01. HP pump seizes | | | | | | | | | |
| | 03.02.02. Injector nozzle blocked or partially blocked due to carbon build up. | | | | | | | | | |
| | 03.03.01. Injector needle lift pressure low due to broken or softened spring | | | | | | | | | |
| | 03.03.03. Injector needle, seat, pressure pin worn. | | | | | | | | | |
| CBM: Air-to-air intercooler overhaul: Interval to be established by age exploration. | 11.02.06. Air based intercooler leaking boost air due to fatigue cracking or erosion. | | Diesel Mechanic | 0.251 | 0.05 | NSM: Run to failure. | N/A | 0.05 | 0 | Moderate |
| CBM: Check and adjust valve lash | 09.02.04. Valve disc burnt due to insufficient valve lash. | 1 Years | Diesel Mechanic | 50.2 | 10 | CBM: Check and adjust valve lash | 1 Years | 10 | 0 | None |
| | 09.02.05. Valve fatigue fracture due to excessive valve lash | 1 Years | Diesel Mechanic | | | | | | | |
| CBM: Coolant analysis | 10.01.01. Cylinder liner perforation due to cavitation corrosion | 1 Months | Oil Analysis | 25.1 | 5 | CBM: Coolant analysis | 1 Months | 5 | 0 | None |
| CBM: Cylinder head and strongback inspection, and repair as required, at engine overhaul | 10.01.04. Head gasket leaking due to erosion/corrosion on head and/or strongback | 33750 MWHrs | Diesel Mechanic | 50 | 25 | CBM: Cylinder head and strongback inspection, and repair as required, at engine overhaul | 33750 MWhrs | 25 | 0 | None |
| CBM: Cylinder liner inspection and qualification at engine overhaul | 09.01.02. Cylinder liner wears allowing excessive blow-by | 33750 MWHrs | Diesel Mechanic | 25.1 | 5 | CBM: Cylinder liner inspection and qualification at engine overhaul | 33750 MWhrs | 5 | 0 | None |
| CBM: Detailed hose inspection | 04.01.02. Hose rubs through due to contact on another component combined with vibration | 3 Months | Diesel Mechanic | 10.3 | 0.2 | CBM: Detailed hose inspection | 4 months | 0.2 | 0 | None |
| | 04.01.03. Rubber hose cracks or splits due to perished rubber | 3 Months | Diesel Mechanic | | | | | | | |
| CBM: Detailed hose inspection for wear and rubbing | 04.01.01. Flexible Fuel return hose rubs through against compressed air pipe below the platform level | 3 Months | Diesel Mechanic | 50.2 | 5.05 | CBM: Detailed hose inspection for wear and rubbing | 4 months | 5.05 | 0 | None |
| CBM: Drain a small amount of fuel from the bottom of the fuel tank to check for water. | 01.08.01. Moisture condenses in the fuel tank, contaminating the fuel | 6 Months | Diesel Mechanic | 25.1 | 5 | NSM: Run to fail | N/A | 25.1 | 20.1 | Minor |
| CBM: Engine load test inspection | 09.03.01. Decompression plug washer failed | 3 Months | Diesel Mechanic | 0.1 | 0.05 | No current maintenance procedures require this step. | 4 months | 0.05 | 0 | None |
| CBM: Fuel sampling | 09.02.02. Valve corroded due to combustion by-products | 6 Months | Oil Analysis | 5 | 5 | CBM: Fuel sampling | 6 Months | 5 | 0 | None |
| CBM: Inspect air-to-air intercooler for dirt or debris accumulation | 11.03.03. Air based intercooler clogged by dirt or debris | 6 Months | Diesel Mechanic | 1 | 0.5 | CBM: Inspect air-to-air intercooler for dirt or debris accumulation | 4 months | 0.5 | 0 | None |
| CBM: Inspect and repair as necessary on engine overhaul | 10.01.09. Valve guide worn due to normal wear | 33750 MWhrs | Diesel Mechanic | 10 | 5 | CBM: Inspect and repair as necessary on engine overhaul | 33750 MWhrs | 5 | 0 | None |

Figure K.1: Analysis recommendations, part 1

| Recommendation Headline | Failure Mode Id | Recommended Interval | Recommended Resource Description | Total Unmitigated Risk | Total Mitigated Risk | Current Maintenance Task | Current Task Interval | Current Risk | Risk Delta (Current Risk-Total Mitigated Risk) | Change Level |
|---|---|---|---|---|---|---|---|---|---|---|
| CBM: Inspect the intercooler tell-tale for leaks | 13.01.04. Water based intercooler leaking coolant due to cavitation | 3 Months | Diesel Mechanic | 100 | 0.2 | CBM: Inspect the intercooler tell-tale for leaks | 4 months | 0.2 | 0 | None |
| | 13.01.05. Water Based Intercooler leaking coolant due to fatigue cracking | 3 Months | Diesel Mechanic | | | | | | | |
| CBM: Inspect turbo supply line for missing spacers and signs of rubbing and leaking. | 13.01.01. Turbo oil supply line perforated. | 3 Months | Diesel Mechanic | 50 | 50 | CBM: Inspect turbo supply line for missing spacers and signs of rubbing and leaking. | 4 months | 50 | 0 | None |
| CBM: Inspect turbocharger discharge piping for leaks while the locomotive is self-loading. | 11.02.01. Turbo discharge o-ring leaking boost air | 3 Months | Diesel Mechanic | 0.502 | 0.1 | CBM: Inspect turbocharger discharge piping for leaks while the locomotive is self-loading. | 4 months | 0.1 | 0 | None |
| | 11.02.09. WBIC inlet flange o-ring leaking | 3 Months | Diesel Mechanic | | | | | | | |
| CBM: Load test: Check fuel pressure | 01.02.01. Fuel transfer pump vanes worn | 3 Months | Diesel Mechanic | 0.2 | 0.1 | CBM: Load Test: Check fuel pressure | 4 months | 0.1 | 0 | Minor |
| | 01.02.02. Return fuel pressure regulating valve is out of adjustment. | 3 Months | Diesel Mechanic | | | | | | | |
| CBM: Measure cylinder liner wear | 06.01.06. Piston sealing ring land or piston skirt cracked due to excessive piston-cylinder clearance | 33750 MWHrs | Diesel Mechanic | 10 | 5 | CBM: Measure cylinder liner wear | 33750 MWHrs | 5 | 0 | None |
| CBM: Measure piston wear at overhaul | 06.01.04. Piston skirt wear allowing misalignment and overloading | 33750 MWHrs | Diesel Mechanic | 25.1 | 0.05 | SCH: Piston replacement at overhaul | 33750 MWHrs | 0.05 | 0 | None |
| CBM: Oil analysis | 02.02.04. Fuel Pump Roller Cracked | 7 Days | Diesel Mechanic | 203.61 | 107.2 | CBM: Oil Analysis | 7 Days | 107.2 | 0 | None |
| | 06.01.02. Piston and Cylinder seizure due to oil starvation | 7 Days | Diesel Mechanic | | | | | | | |
| | 07.01.07. Crosshead roller cracked due to introduced defect | 7 Days | Oil Analysis | | | | | | | |
| | 08.02.01. Bearing seizure due to cavitation damage | 7 Days | Oil Analysis | | | | | | | |
| | 08.02.05. Bearing failure due to assembly error | 7 Days | Oil Analysis | | | | | | | |
| | 09.01.01. Cylinder liner accelerated wear | 7 Days | Oil Analysis | | | | | | | |
| | 10.01.01. Cylinder liner perforation due to cavitation corrosion | 7 Days | Oil Analysis | | | | | | | |
| | 10.01.03. Cylinder liner shoulder seal fails prematurely | 7 Days | Oil Analysis | | | | | | | |
| CBM: Turbine disc inspection at overhaul | 11.01.09. Turbine disc is eroded due to particles in the exhaust gas | 33750 MWHrs | Diesel Mechanic | 25 | 25 | CBM: Turbine disc inspection at overhaul | 33750 MWHrs | 25 | 0 | None |
| CBM: Turbo inlet duct to be inspected for signs of cracking or leaks | 12.01.04. Turbo inlet duct cracked due to rubber ageing | 6 Months | Diesel Mechanic | 50 | 25 | CBM: Turbo inlet duct to be inspected for signs of cracking or leaks | 4 months | 25 | 0 | None |
| DSN: Install a rain drain on the turbocharger | 11.01.06. Turbo washed by rain water; goes out of balance | | | 50 | 25 | DSN: Install a rain drain on the turbocharger | N/A | 25 | 0 | None |
| DSN: Install water separator, alarm and dehumidifier breather in low pressure fuel system. | 01.08.01. Moisture condenses in the fuel tank, contaminating the fuel | | | 25.1 | 0.251 | NSM: Run to fail | N/A | 25.1 | 24.849 | Moderate |
| DSN: Modification:elongate holes to allow better alignment. (modification completed) | 11.02.05. Turbo discharge/WBIC flexible duct split due to misalignment | | Diesel Mechanic | 0.251 | 0.05 | DSN: Modification - elongate holes to allow better alignment. (modification completed) | N/A | 0.05 | 0 | None |

Figure K.2: Analysis recommendations, part 2

| Recommendation Headline | Failure Mode Id | Recommended Interval | Recommended Resource Description | Total Unmitigated Risk | Total Mitigated Risk | Current Maintenance Task | Current Task Interval | Current Risk | Risk Delta (Current Risk-Total Mitigated Risk) | Change Level |
|---|---|---|---|---|---|---|---|---|---|---|
| DSN: OEM Redesign in progress | 01.07.02. Hot return fuel from engine entering fuel tank directly next to fuel intake. | | | 2.51 | 0.251 | DSN: OEM Redesign in progress | N/A | 0.251 | 0 | None |
| DSN: OEM to redesign turbocharger bearings. | 11.01.02. Turbo bearing failure due to overload | | | 125.5 | 25 | DSN: OEM to redesign turbocharger bearings. | N/A | 25 | 0 | None |
| DSN: OEM to redesign turbocharger compressor wheel. | 11.01.04. Turbo compressor wheel high cycle fatigue failure due to vibration resonance. | | | 125.5 | 25 | DSN: OEM to redesign turbocharger compressor wheel. | N/A | 25 | 0 | None |
| DSN: Redesign fuel bracket to use a thicker steel. | 04.01.08. Low pressure fuel hose bracket broken due to fatigue. | | | 10.1 | 5.05 | Redesign complete. | N/A | 5.05 | 0 | None |
| DSN: Redesign fuel injection mapping | 02.01.02. Fuel is not timed correctly causing harsh combustion and overloading | | Diesel Mechanic | 100 | 5 | DSN: Redesign complete. | N/A | 5 | 0 | None |
| DSN: Redesign may be desirable. (completed by OEM) | 10.01.06. Head stud broken due fatigue cracking | | | 10 | 5 | DSN: Redesign may be desirable. (completed by OEM) | N/A | 5 | 0 | None |
| DSN: Redesign to use either hard piping or secure the hose in a suitable manner. | 04.01.01. Flexible Fuel return hose rubs through against compressed air pipe below the platform level | | | 50.2 | 25.35 | CBM: Detailed hose inspection for wear and rubbing | 4 months | 25.35 | 0 | Moderate |
| DSN: Redesign turbo to be resistant to thermal fatigue cracking | 11.02.03. Turbo inlet flange cracked due to cyclical thermal stress fatigue | | | 50 | 25 | NSM: Run to failure. (Turbo redesign not within RTIO control) | N/A | 50 | 25 | None |
| DSN: Replace the flanges on 8140-8156 with an upgraded, thicker version. | 11.02.07. 8.5" Aluminium Air to Air Intercooler Inlet flange cracked due to fatigue | | Diesel Mechanic | 0.251 | 0.05 | NSM: Run to failure. | N/A | 0.251 | 0.201 | Minor |
| NSM: Run to fail | 10.01.10. Rocker cover cracked. Root cause unknown - likely to be secondary damage. | | | 0.5 | 0.5 | NSM: Run to fail | N/A | 0.5 | 0 | None |
| NSM: Run to fail, redesign may be desirable. | 07.01.01. Pushrod snapped. Root cause unknown. | | | 10 | 10 | NSM: Run to fail | N/A | 10 | 0 | None |
| NSM: Run to failure. | 11.02.03. Turbo inlet flange cracked due to cyclical thermal stress fatigue | | | 50 | 50 | NSM: Run to failure. | N/A | 50 | 0 | None |
| PROC: All baggy air filters to be delivered packaged and not removed from packaging until installation | 12.01.01. Baggy air filter exterior is contaminated by debris | | | 50 | 25 | PROC: All baggy air filters to be delivered packaged and not removed from packaging until installation | N/A | 25 | 0 | None |
| PROC: All work procedures involving opening of the baggy air filters, turbo, exhaust, ducting to specify check for foreign objects prior to closure. | 11.01.07. Foreign object strikes turbine disc or compressor wheel. | | | 25 | 25 | PROC: All work procedures involving opening of the baggy air filters, turbo, exhaust, ducting to specify check for foreign objects prior to closure. | N/A | 25 | 0 | None |
| PROC: Ensure head studs are screwed in and tensioned when replacing power assembly. | 10.01.07. Head stud broken due to fatigue due to too many exposed threads. | | | 10 | 5 | PROC: Ensure head studs are screwed in and tensioned when replacing power assembly. | N/A | 5 | 0 | None |
| PROC: Inspect piston sealing ring grooves when replacing piston sealing rings. | 06.01.07. Piston sealing ring broken due to incorrect fitment. | | Diesel Mechanic | 10 | 5 | PROC: Inspect piston sealing ring grooves when replacing piston sealing rings. | N/A | 5 | 0 | None |
| PROC: Locomotive welding procedure to specify earthing requirements to prevent stray currents. | 08.02.04. Bearing failure due to electrical discharge | | | 50 | 50 | PROC: Locomotive welding procedure to specify earthing requirements to prevent stray currents. | N/A | 50 | 0 | None |
| PROC: Locomotives not to be restricted to yard duties for longer than 2 weeks | 03.02.02. Injector nozzle blocked or partially blocked due to carbon build up. | | | 15.1 | 10.05 | Acoustic Emissions not currently employed. | N/A | 15.1 | 5.05 | None |
| | 06.01.09. Piston seizes due to lack of lubrication due to glazed bore | | | | | | | | | |
| | 09.02.10. Valve stem seizure due to gum build-up due to excessive idling | | | | | | | | | |

Figure K.3: Analysis recommendations, part 3

| Recommendation Headline | Failure Mode Id | Recommended Interval | Recommended Resource Description | Total Unmitigated Risk | Total Mitigated Risk | Current Maintenance Task | Current Task Interval | Current Risk | Risk Delta (Current Risk-Total Mitigated Risk) | Change Level |
|---|---|---|---|---|---|---|---|---|---|---|
| PROC: Locomotives to be left running during rain events | 11.01.06. Turbo washed by rain water; goes out of balance | | | 50 | 25 | PROC: Locomotives to be left running during rain events | N/A | 25 | 0 | None |
| PROC: Long power assembly replacement procedure to include requirement to check connecting rod for damage sustained during handling. | 08.01.02. Premature connecting rod fatigue failure | | | 105.1 | 105.1 | PROC: RTIO to audit vendor work quality at engine overhauls | N/A | 105.1 | 0.05 | Minor |
| PROC: Procedure to advise maintainer of the potential fitting error when installing valve bridges. | 07.01.02. Valve bridge loose; fitted incorrectly | | | 10 | 5 | PROC: Procedure to advise maintainer of the potential fitting error when installing valve bridges. | N/A | 5 | 0 | None |
| PROC: Procedure to advise maintainer that whenever the decompression plug is removed, the decompression washer can easily fall out. | 09.03.01. Decompression plug washer failed | | | 0.1 | 0.05 | No current maintenance procedures require this step. | N/A | 0.05 | 0 | Minor |
| PROC: Procedure to ensure detailed assembly instructions are supplied. | 10.01.05. Head gasket leaking due to poor assembly. | | | 10 | 5 | PROC: Procedure to ensure detailed assembly instructions are supplied. | N/A | 5 | 0 | None |
| PROC: Procedure to include a requirement to mark each bolt as it is torqued to specification | 07.01.04. Valve tappet loose; not torqued properly | | | 20 | 10 | PROC: Procedure to include a requirement to mark each bolt as it is torqued to specification | N/A | 10 | 0 | None |
| | 07.01.05. Valve train rocker shaft bolts come loose due to insufficient torque. | | | | | | | | | |
| PROC: Procedure to specify critical inspection locations | 04.01.01. Flexible Fuel return hose rubs through against compressed air pipe below the platform level | | | 60.5 | 15.15 | CBM: Detailed hose inspection for wear and rubbing | 4 months | 60.5 | 45.35 | Minor |
| | 04.01.02. Hose rubs through due to contact on another component combined with vibration | | | | | | | | | |
| | 04.01.03. Rubber hose cracks or splits due to perished rubber | | | | | | | | | |
| PROC: Procedure to specify ring spanner tool | 07.01.03. Valve tappet loose; not fully torqued due to open ended spanner fouling | | | 10 | 5 | PROC: Procedure to specify ring spanner tool | N/A | 5 | 0 | None |
| PROC: Procedure to specify the use of a calibrated hydraulic tensioner | 08.01.03. Insufficient bolt pretension causing fatigue cracking in the connecting rod, bolts or bearing. | | | 100.5 | 50.5 | PROC: Procedure to specify the use of a calibrated hydraulic tensioner | N/A | 50.5 | 0 | None |
| PROC: Replace all head studs whenever one head stud fails. | 10.01.08. Head Stud broken due to overloading from previous broken stud. | | | 10 | 5 | PROC: Replace all head studs whenever one head stud fails. | N/A | 5 | 0 | None |
| PROC: Replace O-ring whenever it is disturbed | 11.02.01. Turbo discharge o-ring leaking boost air | | | 0.502 | 0.502 | PROC: Replace O-ring whenever it is disturbed | N/A | 0.502 | 0 | None |
| | 11.02.09. WBIC inlet flange o-ring leaking | | | | | | | | | |
| PROC: Replace the coolant drain seal whenever the turbo is replaced | 13.01.02. Turbo coolant drain seal leaking | | Diesel Mechanic | 0.1 | 0.05 | PROC: Replace the coolant drain seal whenever the turbo is replaced | N/A | 0.05 | 0 | None |
| PROC: Replace the oil drain seal whenever the turbo is replaced | 13.01.03. Turbo oil drain seal leaking | | Diesel Mechanic | 0.1 | 0.05 | PROC: Replace the oil drain seal whenever the turbo is replaced | N/A | 0.05 | 0 | None |
| PROC: RTIO to audit vendor work quality at engine overhauls | 08.01.02. Premature connecting rod fatigue failure | | | 155.1 | 105.1 | PROC: RTIO to audit vendor work quality at engine overhauls | 1 Years | 105.1 | 0 | None |
| | 08.02.05. Bearing failure due to assembly error | | | | | | | | | |
| PROC: RTIO to include instructions on fitting bearings in procedure | 08.02.05. Bearing failure due to assembly error | | | 50 | 50 | PROC: RTIO to include instructions on fitting bearings in procedure | | 50 | 0 | None |
| PROC: Torque verification | 04.01.05. Fuel line joint bolts left loose following maintenance | | Diesel Mechanic | 125.3 | 40 | PROC: Torque verification | N/A | 40 | 0 | None |
| | 05.01.01. Injector is loose, o-ring seals wear due to vibration, permitting coolant to enter the lubricating fuel line | | | | | | | | | |

Figure K.4: Analysis recommendations, part 4

| Recommendation Headline | Failure Mode Id | Recommended Interval | Recommended Resource Description | Total Unmitigated Risk | Total Mitigated Risk | Current Maintenance Task | Current Task Interval | Current Risk | Risk Delta (Current Risk-Total Mitigated Risk) | Change Level |
|---|---|---|---|---|---|---|---|---|---|---|
| PROC: Use hydraulic head stud tensioning tool. | 06.01.05. Piston seizes due to warped cylinder due to uneven head stud torque. | | Diesel Mechanic | 10 | 5 | PROC: Use hydraulic head stud tensioning tool. | N/A | 5 | 0 | None |
| PROC: Use OEM parts only | 04.01.09. Incompatible hose material or fitting is used and fails prematurely. | | Diesel Mechanic | 10.1 | 5.05 | PROC: Use OEM parts only | N/A | 5.05 | 0 | None |
| SCH: HP Pump Replacement | 02.01.01. HP Fuel pump internal seals worn | 17000 MWhrs | Diesel Mechanic | 12.761 | 1.05 | SCH: HP Pump Replacement | 11000 MWhrs | 1.05 | 0 | Moderate |
| | 02.02.01. HP pump seizes | 17000 MWhrs | Diesel Mechanic | | | | | | | |
| | 02.02.05. Pump roller return spring breaks due to fatigue | 17000 MWhrs | Diesel Mechanic | | | | | | | |
| SCH: SCHeduled Injector replacement | 03.02.01. Injector atomising nozzles worn | 7000 MWhrs | Diesel Mechanic | 93.081 | 22.05 | SCH: Scheduled Injector replacement | 7000 MWhrs | 22.05 | 0 | None |
| | 03.03.01. Injector needle lift pressure low due to broken or softened spring | 7000 MWhrs | Diesel Mechanic | | | | | | | |
| | 03.03.02. Injector needle seizes due to excessive wear | 7000 MWhrs | Diesel Mechanic | | | | | | | |
| | 03.03.03. Injector needle, seat, pressure pin worn. | 7000 MWhrs | Diesel Mechanic | | | | | | | |
| | 03.03.04. Needle and seat degraded | 7000 | Diesel Mechanic | | | | | | | |
| | 04.01.04. Injector O-Rings leaking | | Diesel Mechanic | | | | | | | |
| SCH: Bearing replacement at turbo overhaul | 11.01.01. Turbo bearing failure due to fatigue | 33750 MWhrs | Diesel Mechanic | 125.5 | 25 | SCH: Bearing replacement at turbo overhaul | 33750 MWhrs | 25 | 0 | None |
| SCH: Connecting rod unit exchange/refurbishment at engine overhaul | 08.01.01. Connecting rod failure due to fatigue cracking | 33750 MWhrs | Diesel Mechanic | 105 | 55 | SCH: Connecting rod unit exchange/refurbishment at engine overhaul | 33750 MWhrs | 55 | 0 | None |
| SCH: Cylinder liner to be replaced at engine overhaul | 06.01.01. Cylinder liner failure due to fatigue cracking | 33750 MWhrs | Diesel Mechanic | 10 | 5 | SCH: Cylinder liner to be replaced at engine overhaul | 33750 MWhrs | 5 | 0 | None |
| SCH: Fuel Transfer Pump Replacement | 01.01.01. Fuel transfer pump fails | 17000 MWhrs | Diesel Mechanic | 2.51 | 0.251 | SCH: Fuel transfer pump replacement | 11000 MWhrs | 0.251 | 0 | Moderate |
| SCH: Lubricating oil to be replaced at 6 month intervals. | 09.02.09. Valve stem seizure due to gum build-up due to degraded lubricating oil. | 6 Months | Diesel Mechanic | 10 | 5 | SCH: Lubricating oil to be replaced at 6 month intervals. | 4 months | 5 | 0 | Minor |
| SCH: Piston to be replaced at engine overhaul | 06.01.03. Piston failure due to fatigue cracking | 33750 MWhrs | Diesel Mechanic | 10 | 5 | SCH: Piston to be replaced at engine overhaul | 33750 MWhrs | 5 | 0 | None |
| SCH: Power assembly heads to be replaced at the 3rd engine overhaul. | 09.02.01. Power assembly head cracked due to thermal stress and vibration fatigue cracking | 101250 MWhrs | Diesel Mechanic | 10 | 5 | SCH: Power assembly heads to be replaced at the 3rd engine overhaul. | 101250 MWhrs | 5 | 0 | None |
| SCH: Replace connecting rod bearings | 08.02.02. Bearing failure due to fatigue cracking | 33750 MWhrs | Diesel Mechanic | 251 | 50 | SCH: Replace connecting rod bearings | 33750 MWhrs | 50 | 0 | None |
| SCH: Replace crosshead rollers at engine overhaul. | 07.01.08. Crosshead roller cracked due to fatigue | 33750 MWhrs | Diesel Mechanic | 1 | 0.5 | SCH: Replace crosshead rollers at engine overhaul. | 33750 MWhrs | 0.5 | 0 | None |
| SCH: Replace fuel filters | 01.03.01. Fuel strainer or filters are blocked | 6 Months | Diesel Mechanic | 101 | 5.05 | SCH: Replace fuel filters | 4 months | 5.05 | 0 | Minor |
| | 01.05.01. Fuel filter blocked | 6 Months | Diesel Mechanic | | | | | | | |
| SCH: Replace O-ring at engine overhauls | 10.01.02. Cylinder liner shoulder seal embrittlement/hardening due to exposure to heat and chemical | 33750 MWhrs | Diesel Mechanic | 1 | 0.5 | SCH: Replace O-ring at engine overhauls | 33750 MWhrs | 0.5 | 0 | None |

Figure K.5: Analysis recommendations, part 4

| Recommendation Headline | Failure Mode Id | Recommended Interval | Recommended Resource Description | Total Unmitigated Risk | Total Mitigated Risk | Current Maintenance Task | Current Task Interval | Current Risk | Risk Delta (Current Risk-Total Mitigated Risk) | Change Level |
|---|---|---|---|---|---|---|---|---|---|---|
| SCH: Replace piston sealing rings | 09.01.03. Piston Sealing Rings lost tension or worn | 33750 MWHrs | Diesel Mechanic | 10 | 5 | SCH: Replace piston sealing rings | 33750 MWhrs | 5 | 0 | None |
| SCH: Replace the air-to-air fan bearings | 11.03.01. Air based intercooler fan bearings seized | 33750 MWHrs | | 2.51 | 0.5 | NSM: Run to failure. | N/A | 2.51 | 2.01 | Moderate |
| SCH: Replace the air-to-air fan motor | 11.03.02. Air based intercooler fan failed; insulation broken down causing a ground fault. | 33750 MWHrs | | 2.51 | 0.5 | NSM: Run to failure. | N/A | 2.51 | 2.01 | Moderate |
| SCH: Replace the baggy air filters | 11.01.08. Baggy air filter clogged | 6 Months | | 100 | 5 | SCH: Replace the baggy air filters | 4 months | 5 | 0 | Minor |
| SCH: Replace the intercooler | 13.01.04. Water based intercooler leaking coolant due to cavitation | 33750 MWHrs | Diesel Mechanic | 100 | 50 | SCH: Replace the intercooler | 33750 MWHrs | 50 | 0 | None |
| | 13.01.05. Water Based Intercooler leaking coolant due to fatigue cracking | 33750 MWHrs | Diesel Mechanic | | | | | | | |
| SCH: Replace valve springs on engine overhaul | 09.02.07. Valve spring fatigue fracture due fretting corrosion between the spring and and cylinder head. | 33750 MWHrs | Diesel Mechanic | 25.1 | 5 | SCH: Replace valve springs on engine overhaul | 33750 MWhrs | 5 | 0 | None |
| SCH: Replace valves at engine overhaul. | 09.02.06. Valve fatigue fracture initiated by fretting corrosion between the valve stem and valve stem keeper. | 33750 MWHrs | Diesel Mechanic | 25.1 | 5 | SCH: Replace at engine overhaul. | 33750 MWhrs | 5 | 0 | None |
| SCH: Scheduled Injector replacement | 03.02.03. Injector seals worn allowing excessive back leagage | 7000 MWHrs | Diesel Mechanic | 2.51 | 0.5 | SCH: Scheduled Injector replacement | 7000 MWHrs | 0.5 | 0 | None |
| SCH: Spin filters to be water cleaned | 12.01.03. Spin filters clogged | 12 Months | Diesel Mechanic | 2.51 | 0.5 | SCH: Spin filters to be water cleaned | 12 Months | 0.5 | 0 | None |
| SCH: Turbo inlet duct to be replaced at engine overhaul | 12.01.04. Turbo inlet duct cracked due to rubber ageing | 33750 MWHrs | | 50 | 25 | SCH: Turbo inlet duct to be replaced at engine overhaul | 33750 MWHrs | 25 | 0 | None |
| TRN: Employ qualified tradesmen | 10.01.05. Head gasket leaking due to poor assembly. | | | 10 | 5 | PROC: Procedure to ensure detailed assembly instructions are supplied. | N/A | 5 | 0 | None |
| TRN: Employ qualified tradesmen. | 01.05.02. Fuel filter damaged, allowing dirt to enter system | | | 10 | 5 | TRN: Employ qualified tradesmen. | N/A | 5 | 0 | None |

Figure K.6: Analysis recommendations, part 4